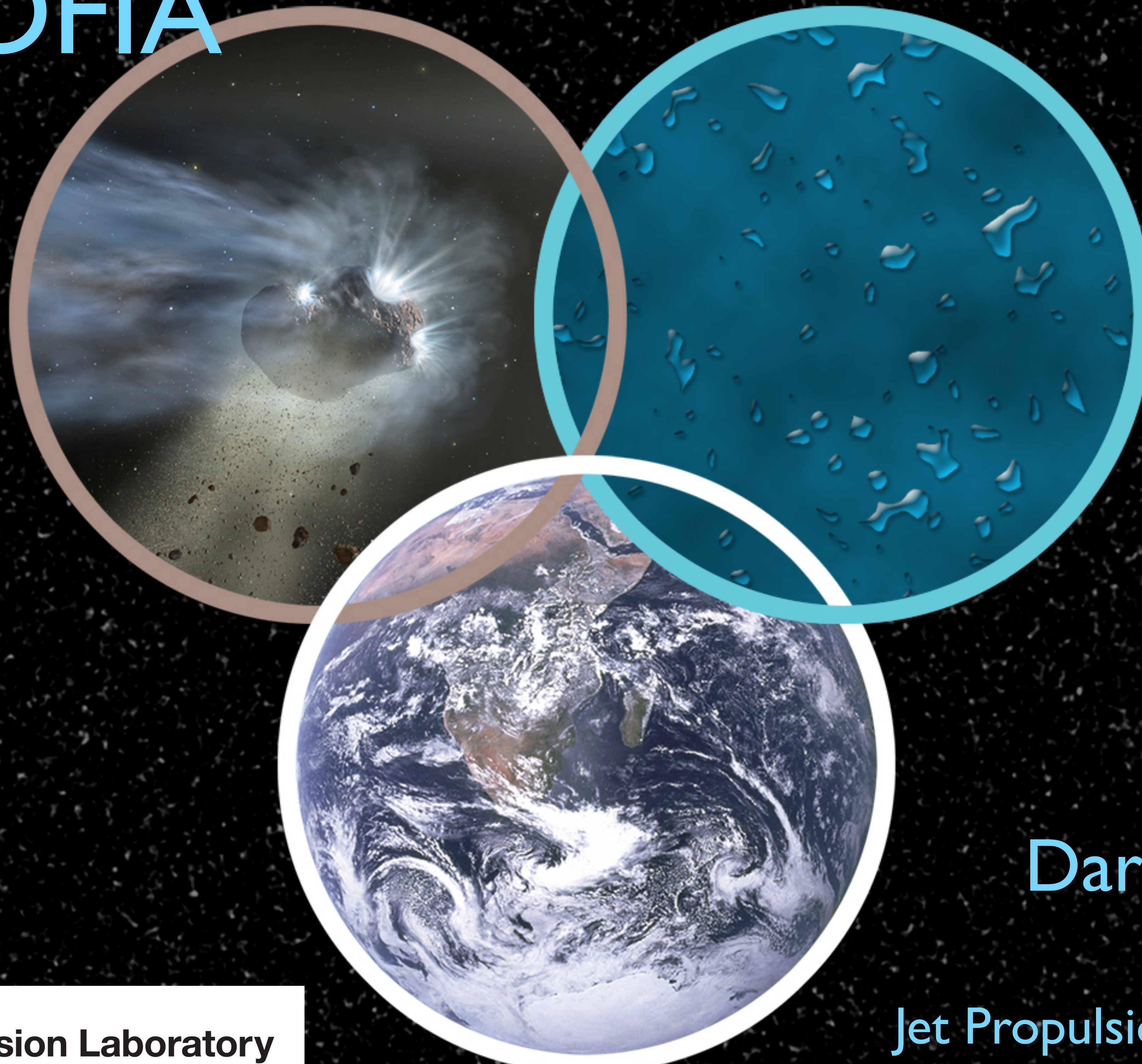
D/H Ratio in the Outer Solar System with SOFIA



Darek Lis

Jet Propulsion Laboratory
California Institute of Technology

AAS Honolulu, January 5, 2020

Jet Propulsion Laboratory
California Institute of Technology

ORIGINS Space Telescope

From first stars to life

SCIENCE DRIVERS FOR MISSION DESIGN

HOW DOES THE UNIVERSE WORK?

How do galaxies form stars, make metals, and grow their central supermassive black holes from reionization to today?

Using sensitive spectroscopic capabilities of a cold telescope in the infrared, Origins will measure properties of star-formation and growing black holes in galaxies across all epochs in the Universe.

HOW DID WE GET HERE?

How do the conditions for habitability develop during the process of planet formation?

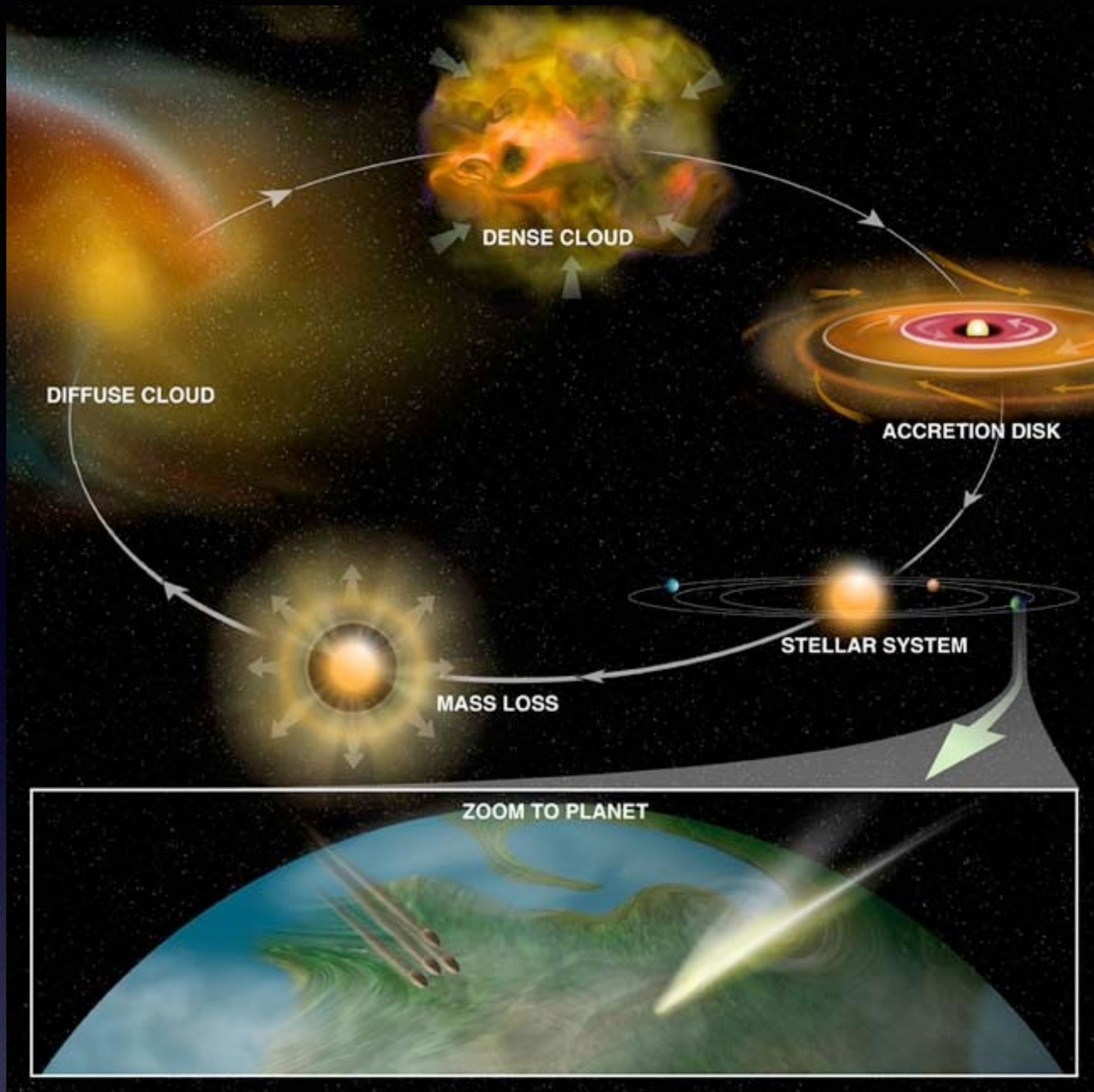
With sensitive and high-resolution far-IR spectroscopy Origins will illuminate the path of water and its abundance to determine the availability of water for habitable planets.

ARE WE ALONE?

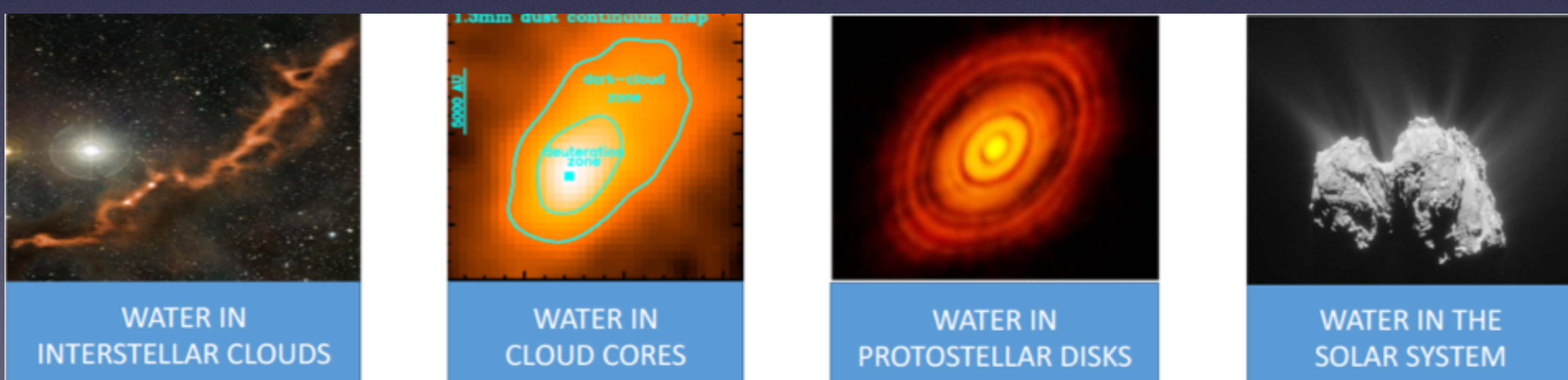
Do planets orbiting M-dwarf stars support life?

By obtaining precise mid-infrared transmission and emission spectra, Origins will assess the habitability of nearby exoplanets and search for signs of life.

- Understand how our Solar System formed and how it is evolving
- Understand how life emerged on Earth and possibly elsewhere in our Solar System

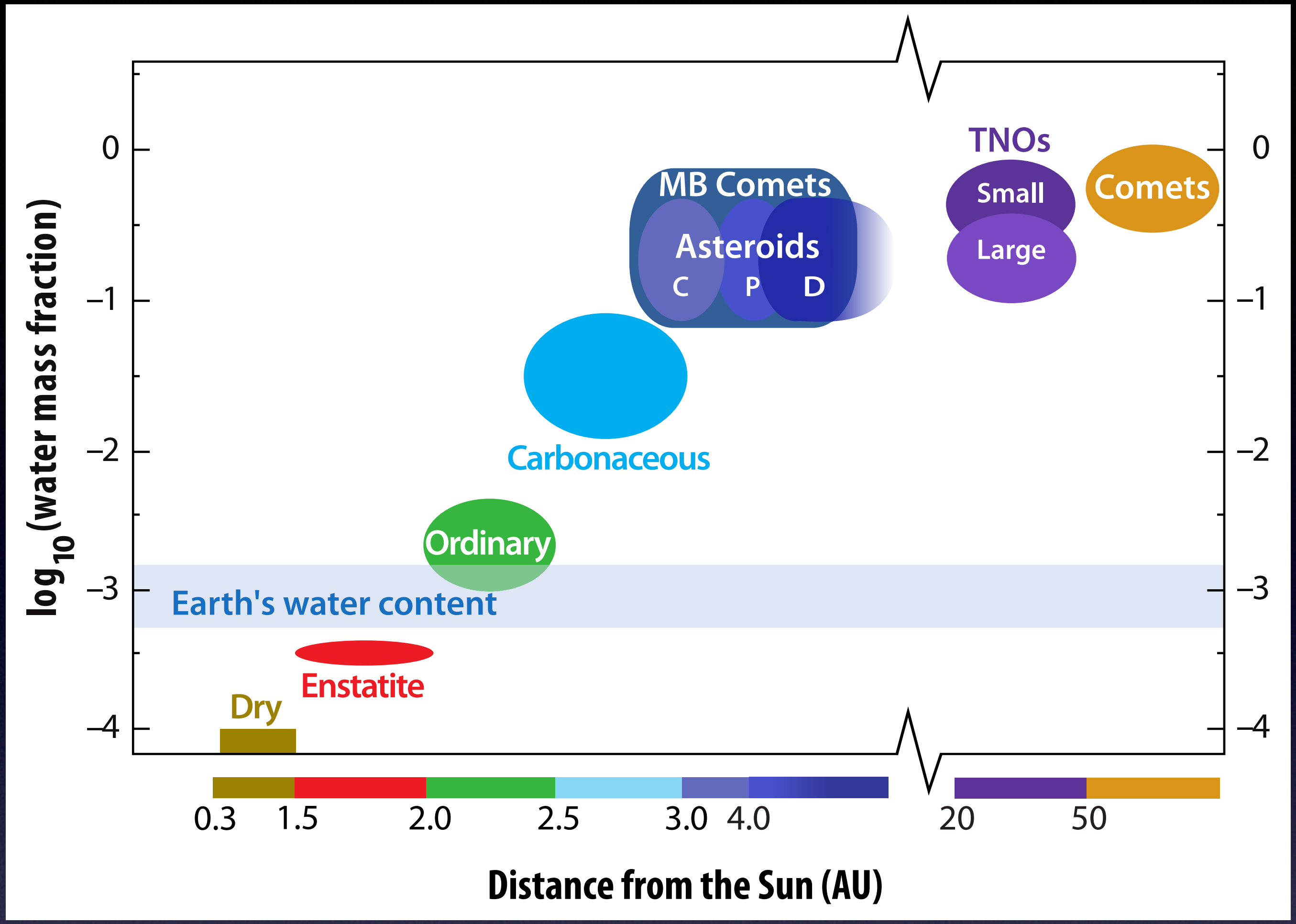


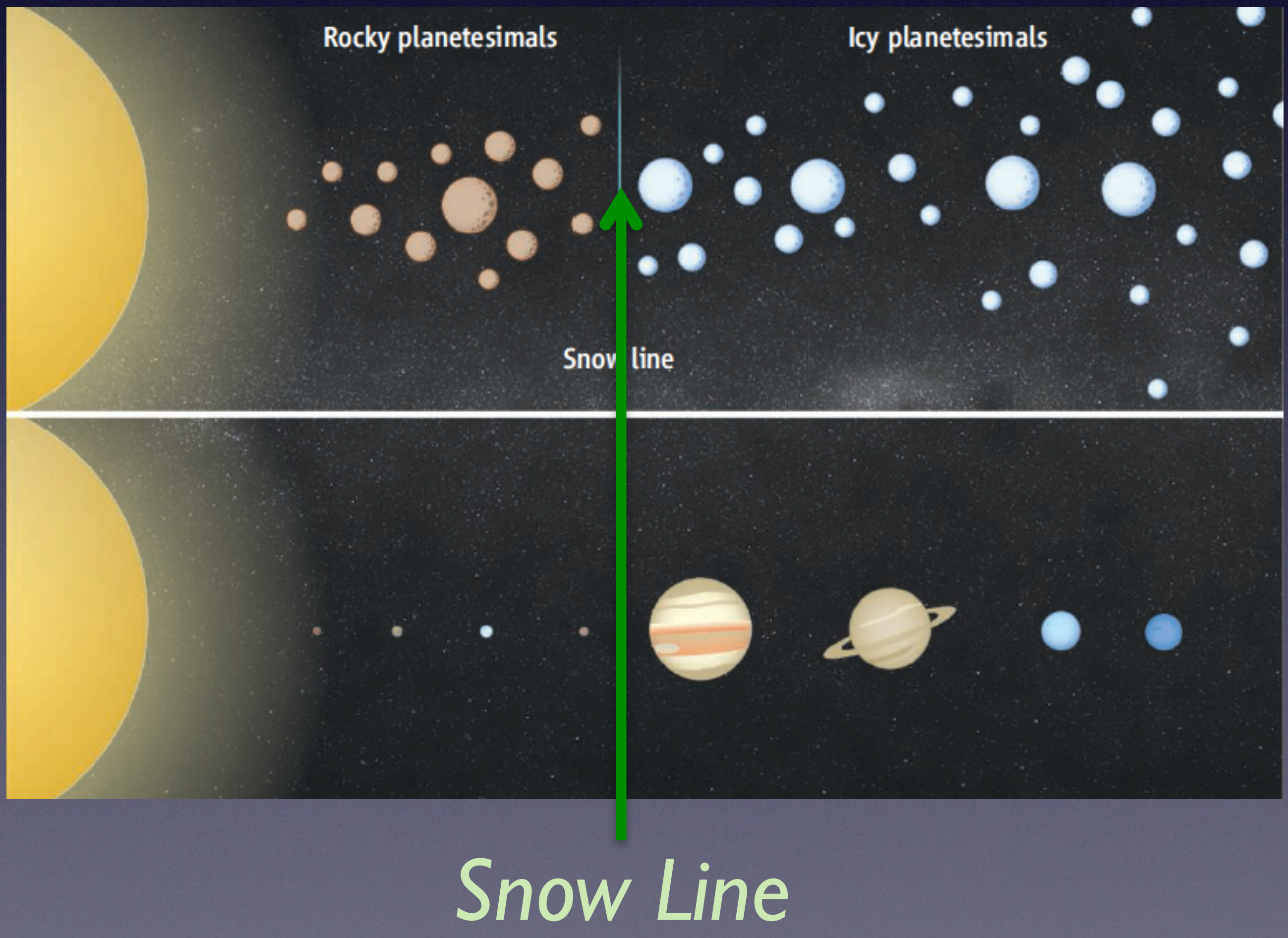
Cosmic Inheritance of Water



- Water trail can be best studied through far-infrared spectroscopy
- Deuteration is a key process for tracing the origin and history of water

Once upon a time the Earth formed dry

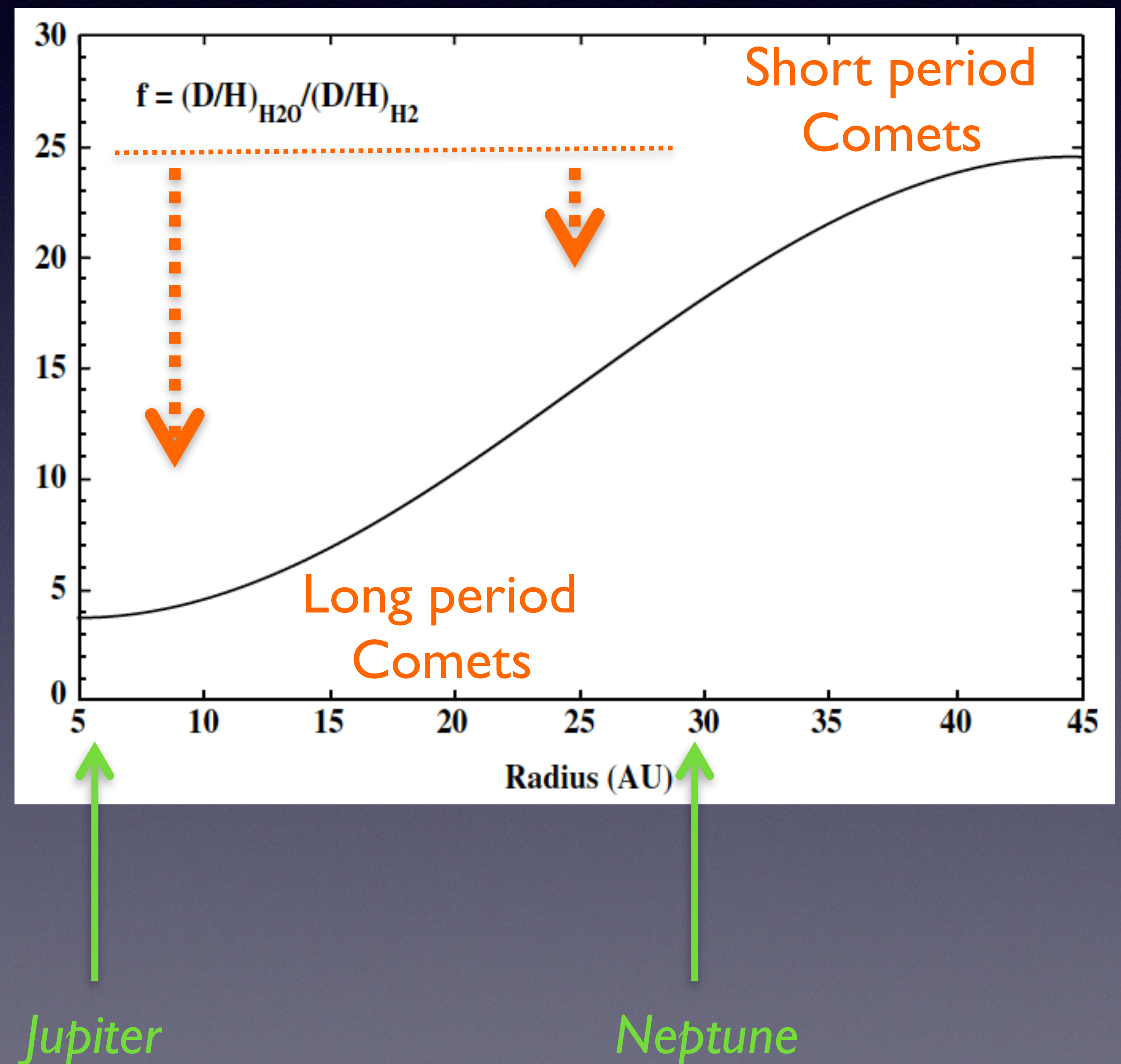




- Water mass fraction increases with distance from the Sun
- "Textbook model": temperature in the terrestrial planet zone too high for water ice to exist
- Water and organics were most likely delivered later by comets or asteroids
- Alternative: water could have survived, incorporated into olivine grains or through oxidation of an early H atmosphere by FeO in the magma ocean

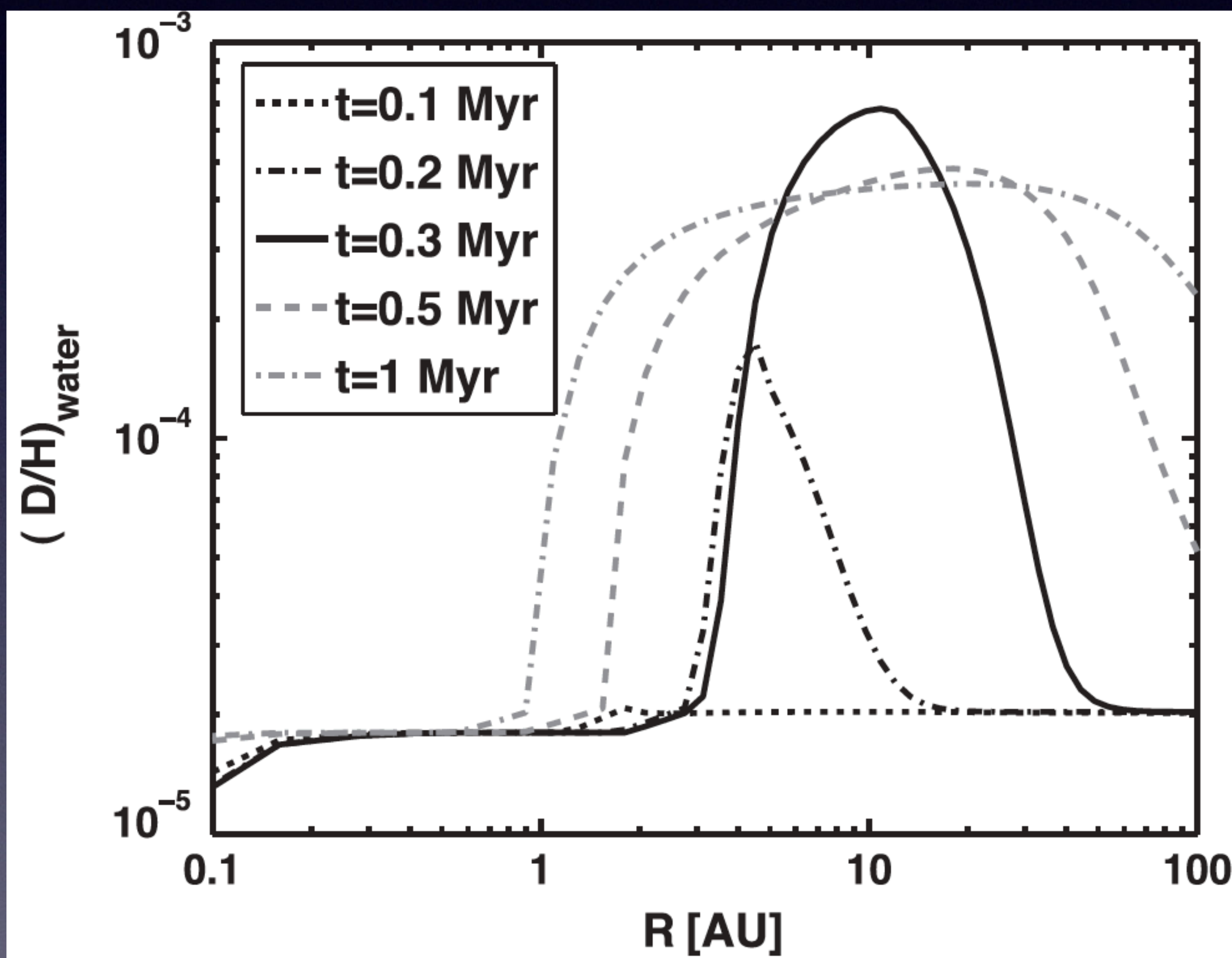
"Textbook" D/H in Water in the Solar Nebula

- Variations in the D/H ratio: progressive isotopic exchange reactions between HDO and H_2
- Water was initially synthesized by interstellar chemistry with a high D/H ratio ($>7.2\times10^{-4}$; highest value measured in clay minerals)
- The D/H ratio in the solar nebula then gradually decreased with time
- Turbulent mixing of grains condensed at different epochs and locations in the solar nebula leads to a D/H gradient



Horner et al. 2007

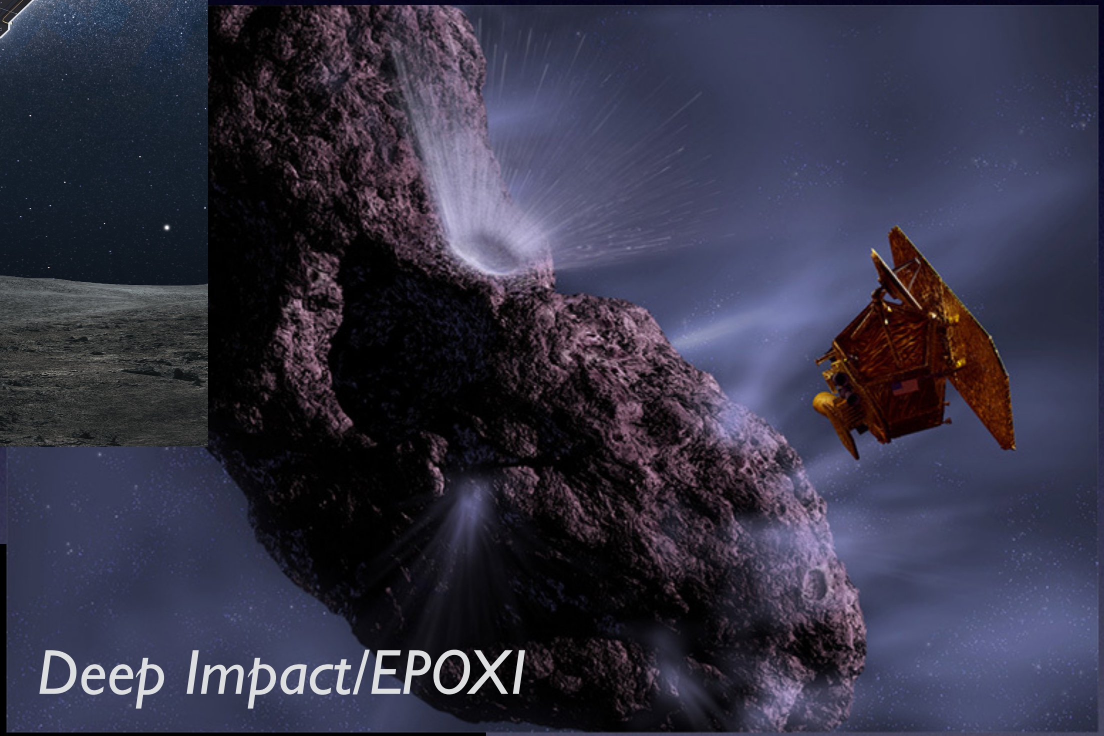
Alternative Models

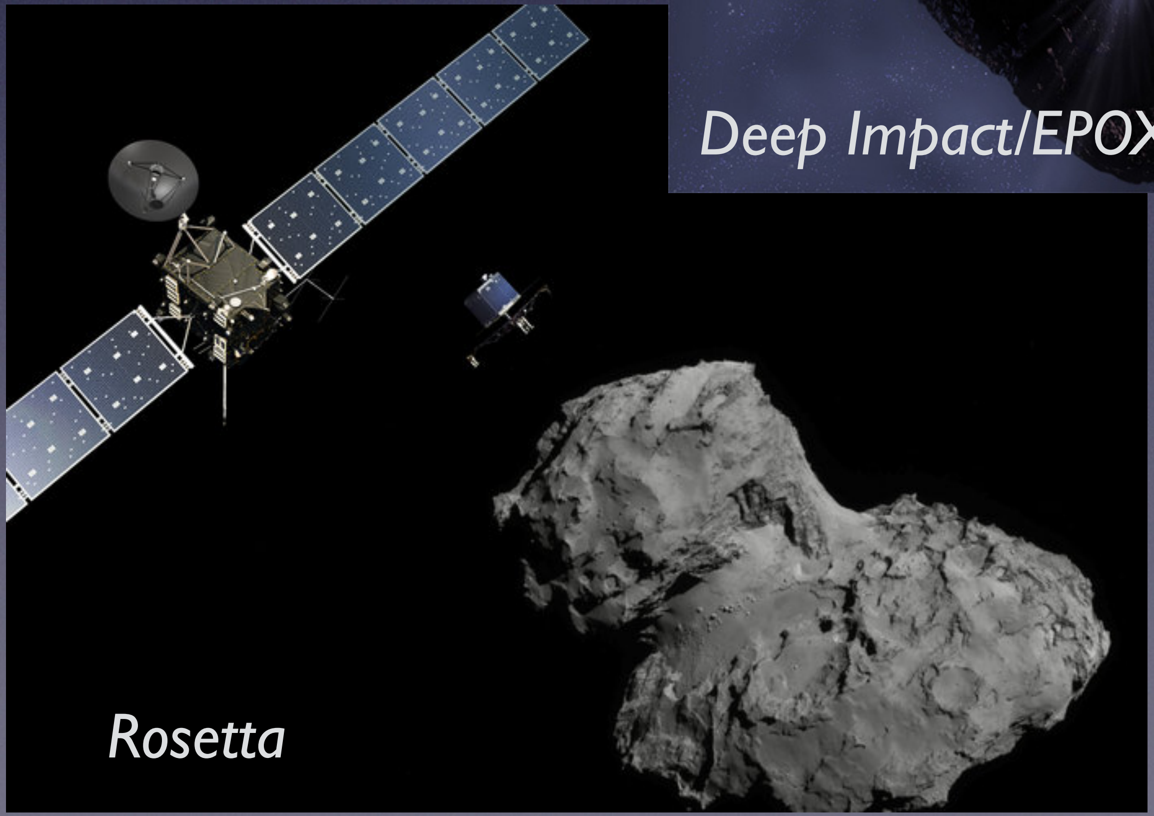


Yang et al. (2013)

- A coupled dynamical and chemical model
- D/H time dependent and may *decrease* in the outer regions
- Water thermally processed in the inner disk transported outward
- Need observational data to test the models, in particular in the outer Solar System

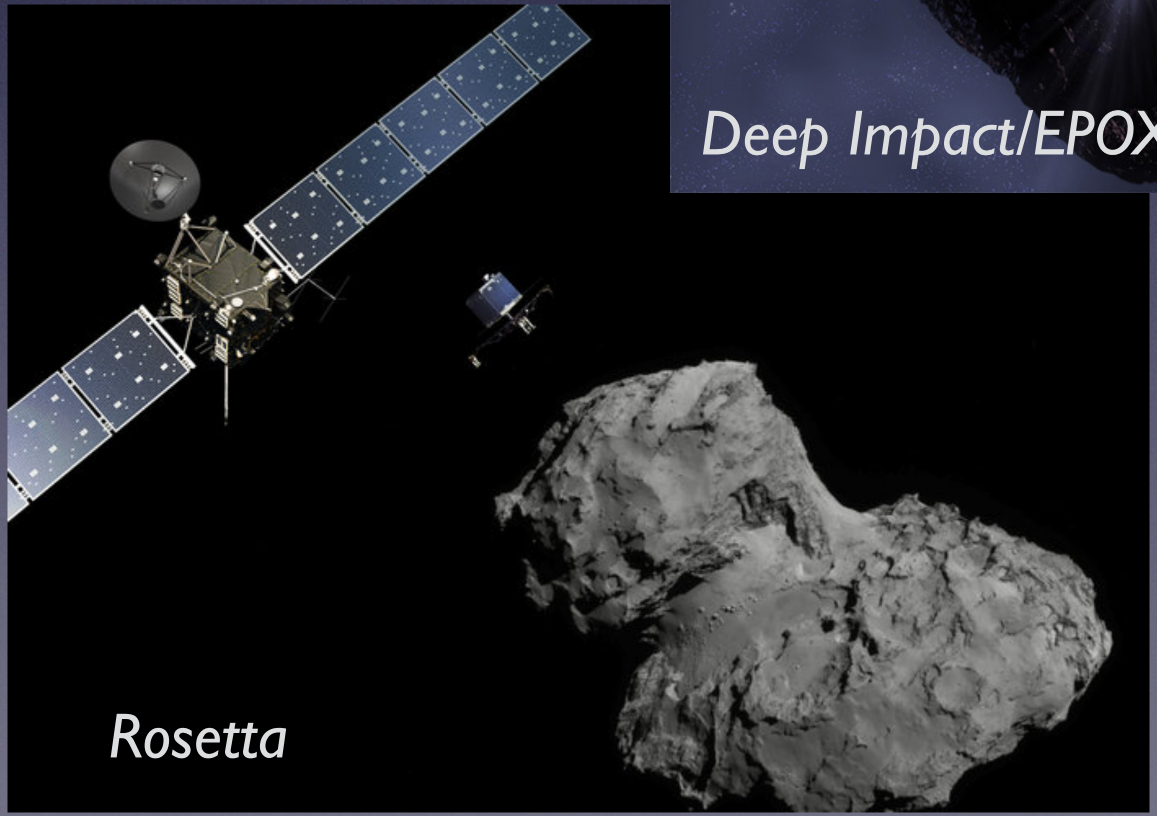
Isotopic Ratio Measurements





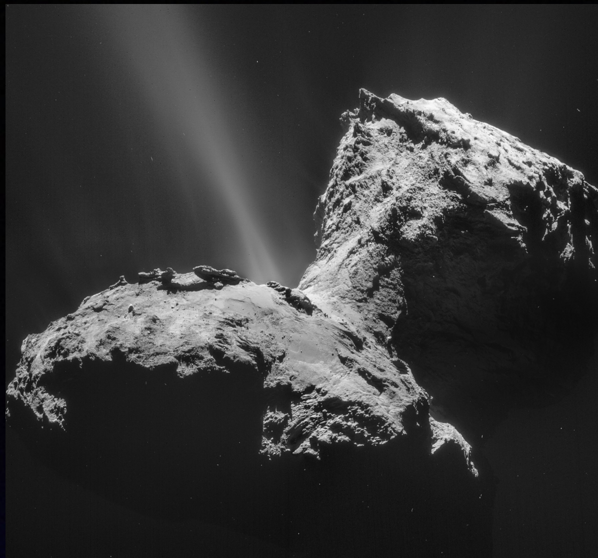
- Sample return or in-situ — detailed studies of individual objects

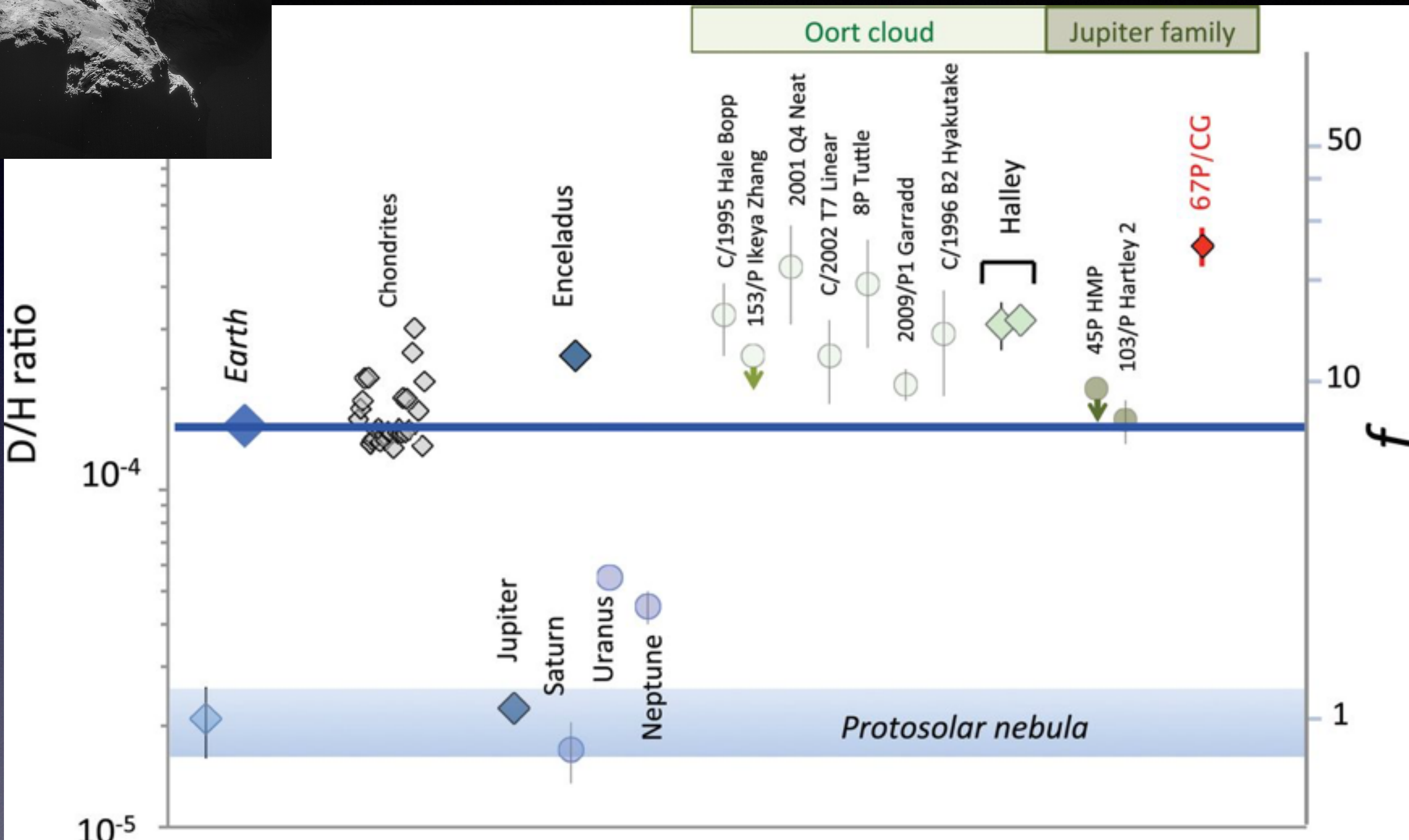
Isotopic Ratio Measurements



- Remote sensing — statistical studies of objects that have atmospheres
- Sample return or in-situ — detailed studies of individual objects

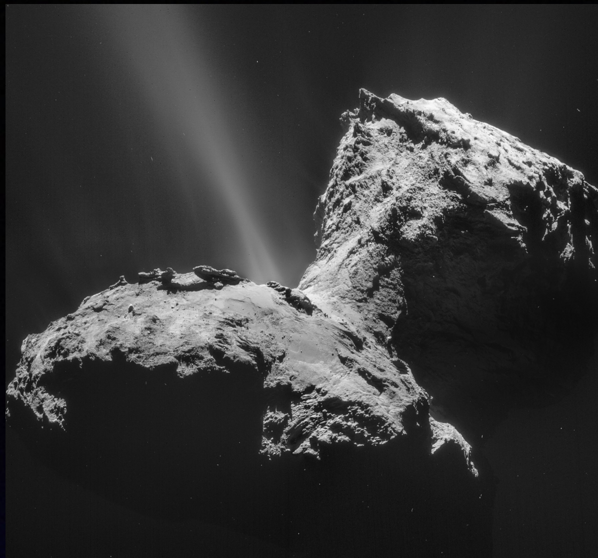
D/H Observations

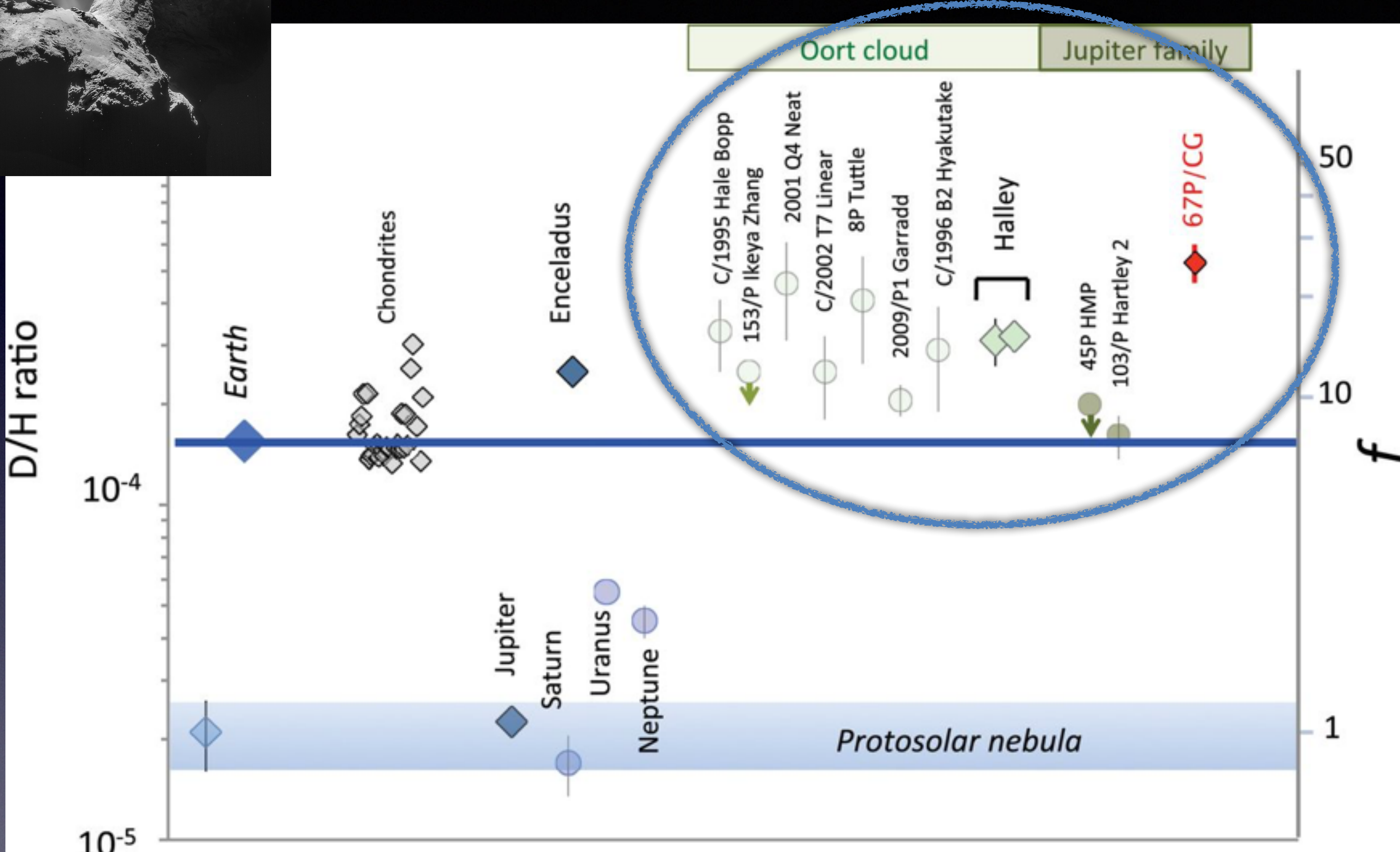




ORIGINS Space Telescope

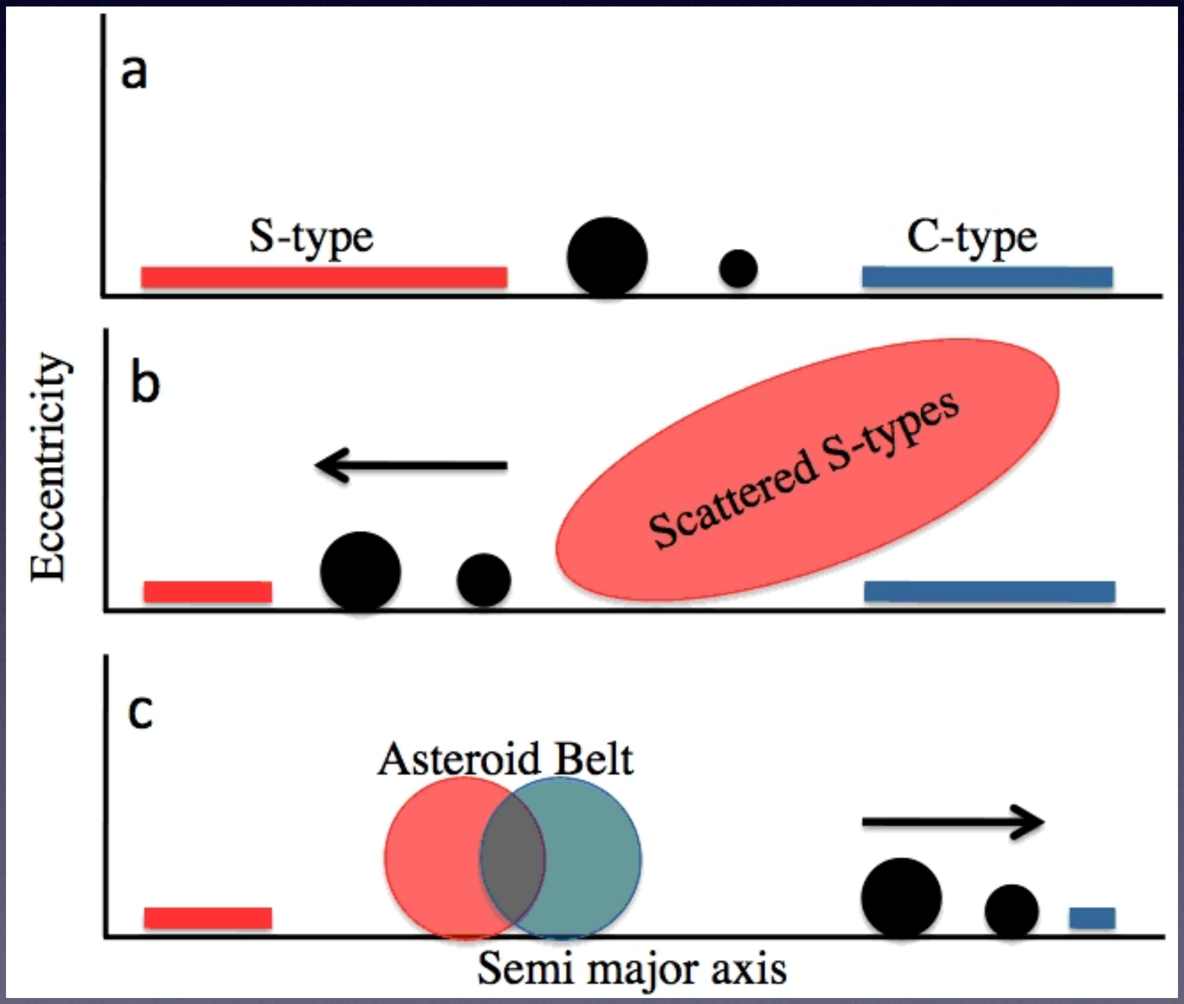
D/H Observations



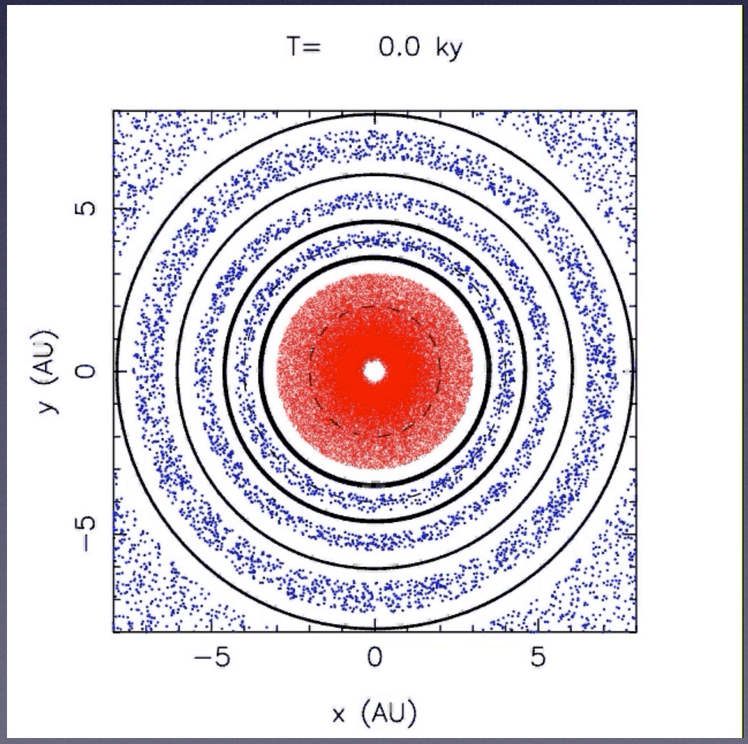


- Comets: variations between one and three times terrestrial value
- No trends with physical or dynamical parameters

Complex Solar System Dynamics: Grand Tack Model

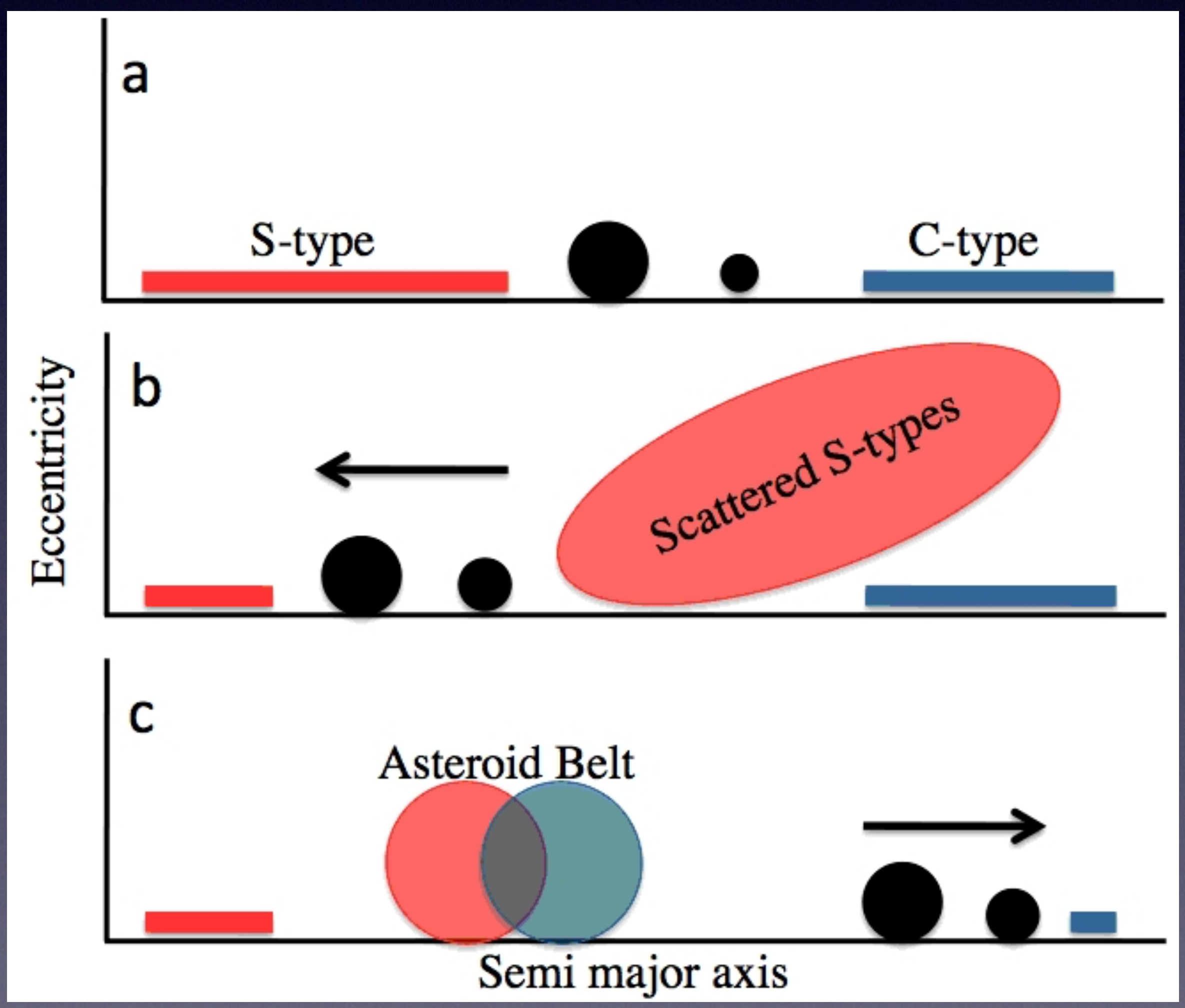


- Inward then outward migration of Jupiter and Saturn leads to complete disappearance of the gas disk
- Happens within first ~5 Myr



Walsh et al. 2011

Complex Solar System Dynamics: Grand Tack Model



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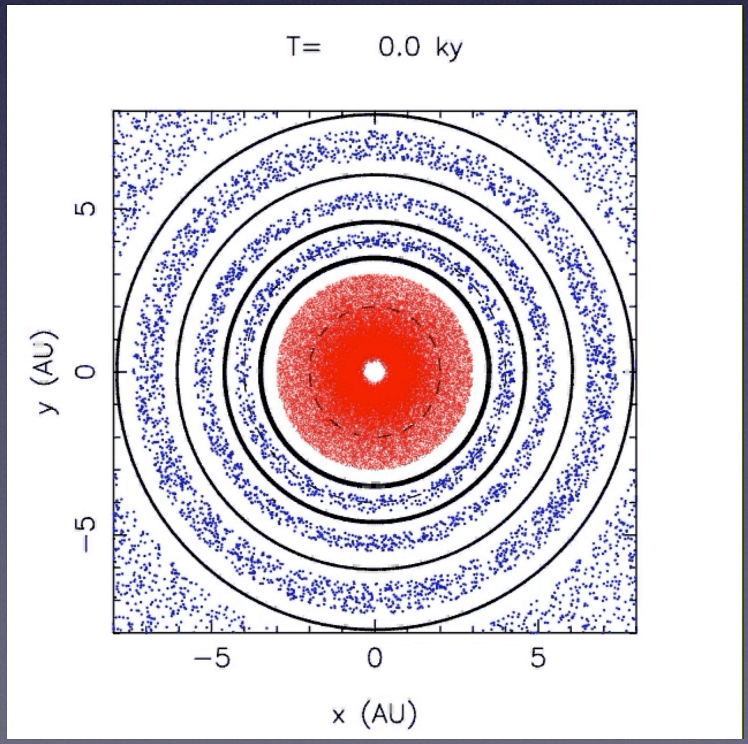
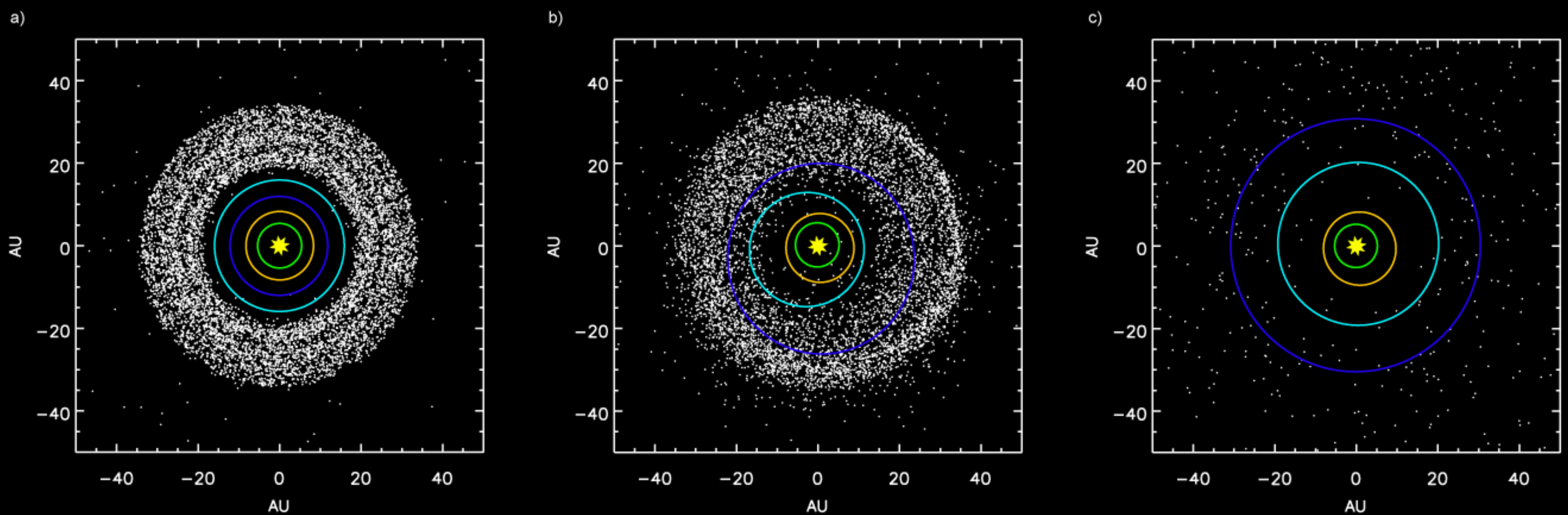


Walsh et al. 2011

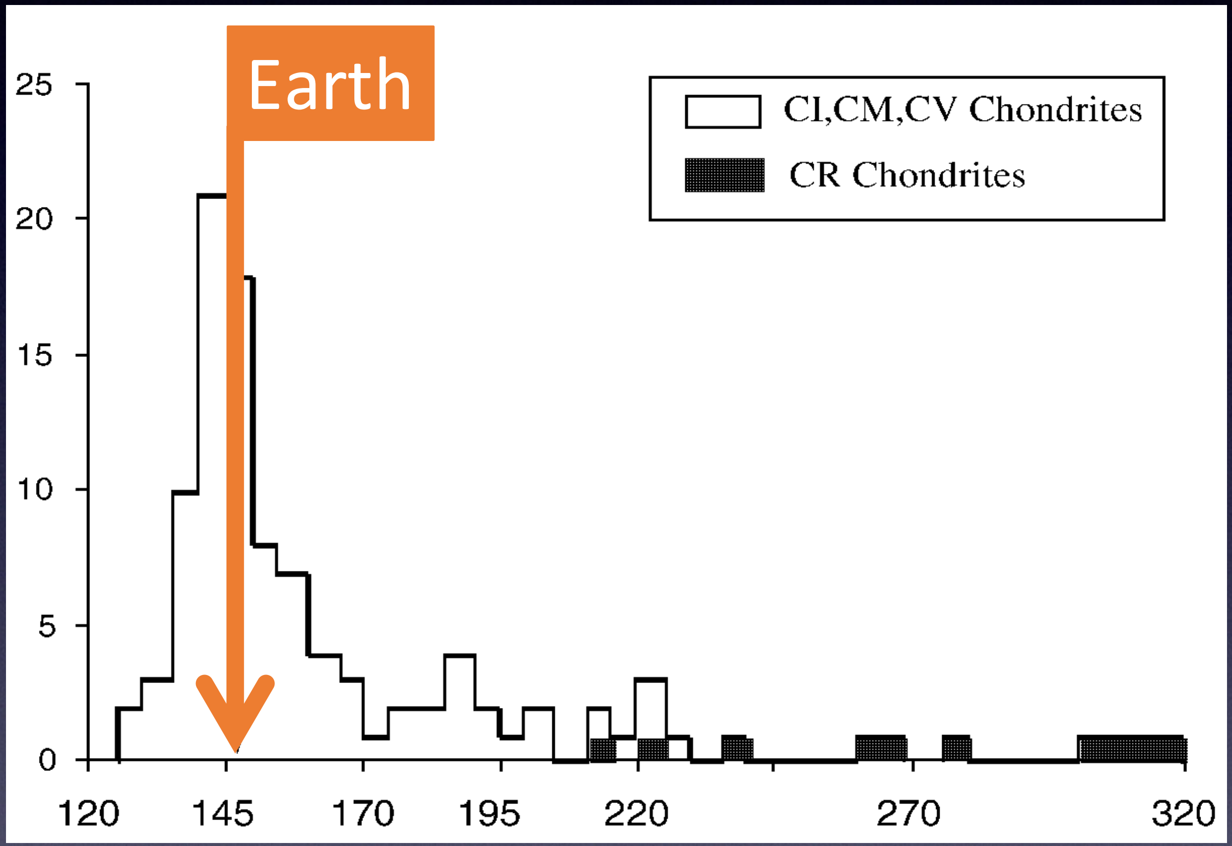
Complex Solar System Dynamics: Nice Model



- Early Solar System much more compact, giant planets on circular orbits
- After ~500 Myr Saturn migrates into 1:2 orbital resonance with Jupiter
- Orbital eccentricities increase destabilizing the planetary system
- Ice giants plough into the planetesimal disk scattering them — Late Heavy Bombardment

Gomes et al. 2005; Tsiganis et al. 2005; Morbidelli et al. 2005

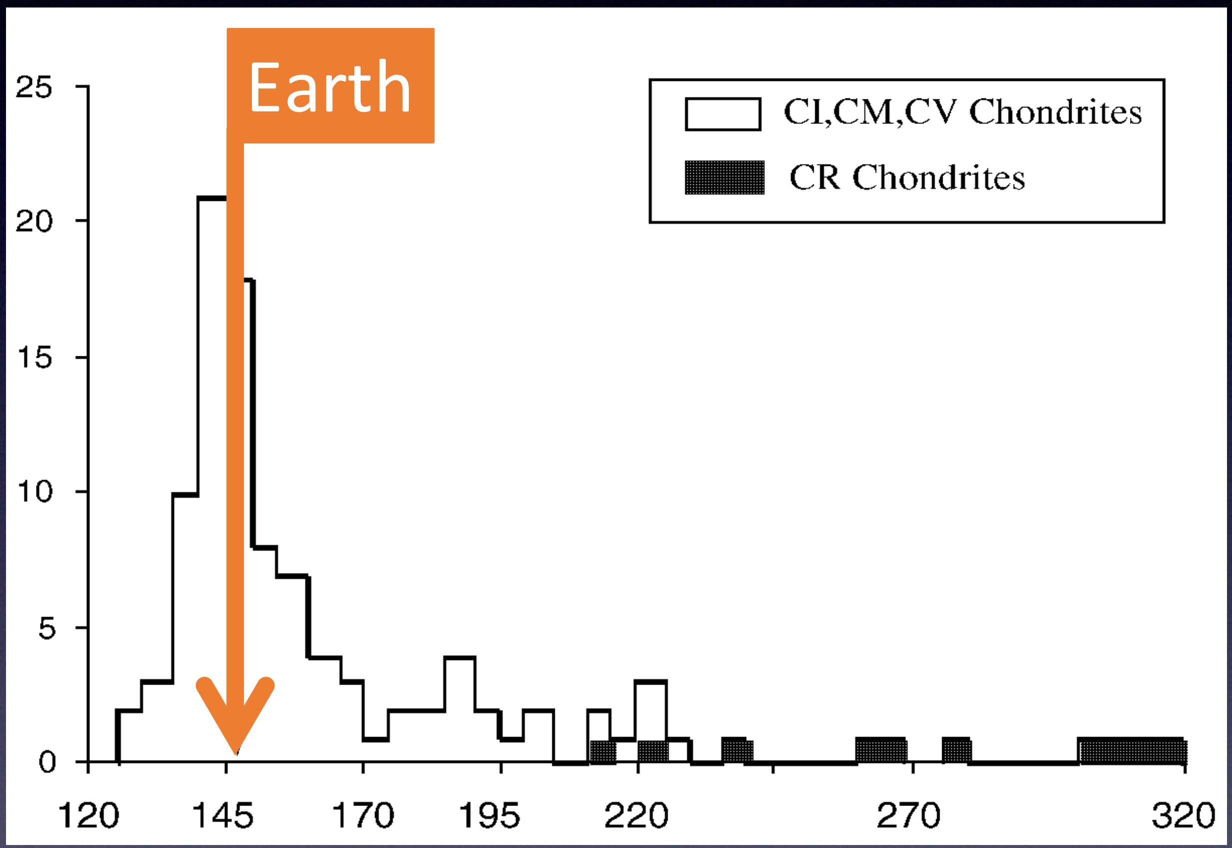
D/H Distribution
Inner vs. Outer Solar System



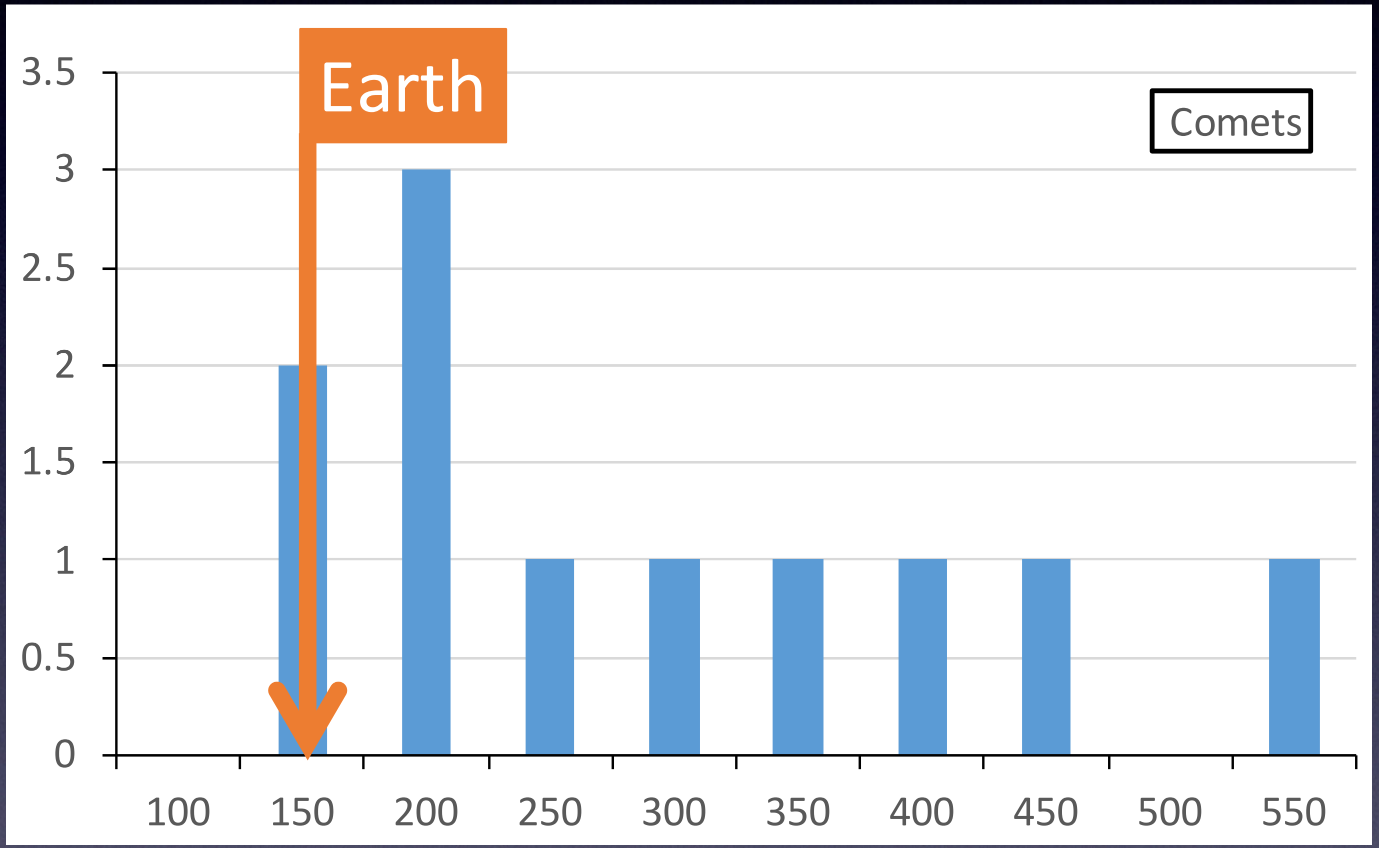
Alexander (2006)

- D/H in the inner Solar System relatively well constrained by measurements in meteorites

D/H Distribution
Inner vs. Outer Solar System



Alexander (2006)



- D/H in the inner Solar System relatively well constrained by measurements in meteorites
- D/H in the outer Solar System poorly constrained — few measurements with large uncertainties

SOFIA/upGREAT+4GREAT

upGREAT	Low Frequency Array : LFA	1810 - 1950	OH lines, [CII],CO series, [OI]	7 x 2 Pixels (2 Pol)	Cryo-Cooler
		1830 - 2070			
	High Frequency Array : HFA	4744	[OI]	7 Pixels	Cryo-Cooler

[CII]

[OI]

Channel	CH1	CH2	CH3	CH4
RF Bandwidth [GHz]	492 – 630	892 – 1100	1200-1500	2490 - 2700
IF Bandwidth [GHz]	4 – 8	4 – 8	0.5 – 3.5	0.5 – 3.5
Mixer	SIS	SIS	HEB	HEB
	Herschel HIFI - 1	Herschel HIFI - 4	GREAT -L1	GREAT - M-HD

[NII] HD

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[OI]

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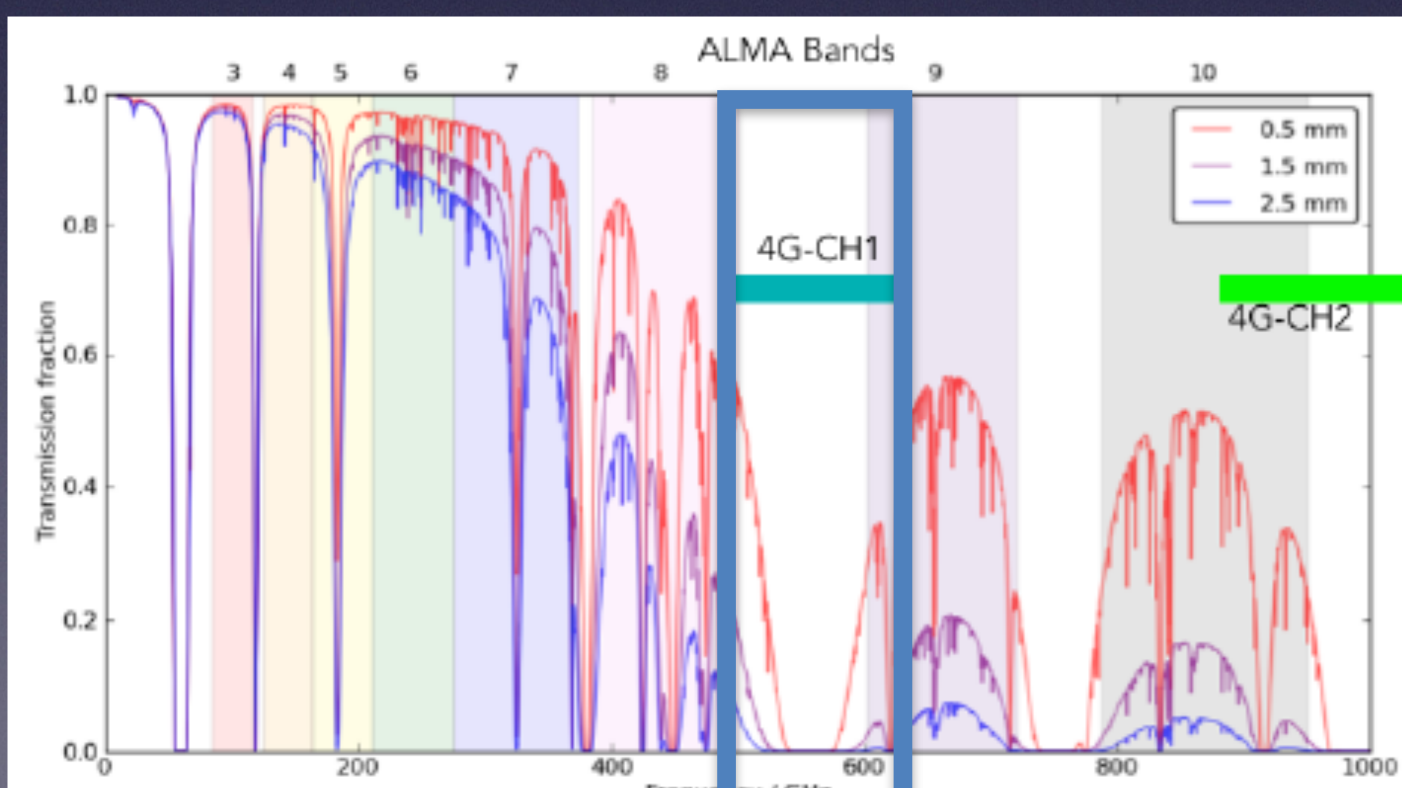
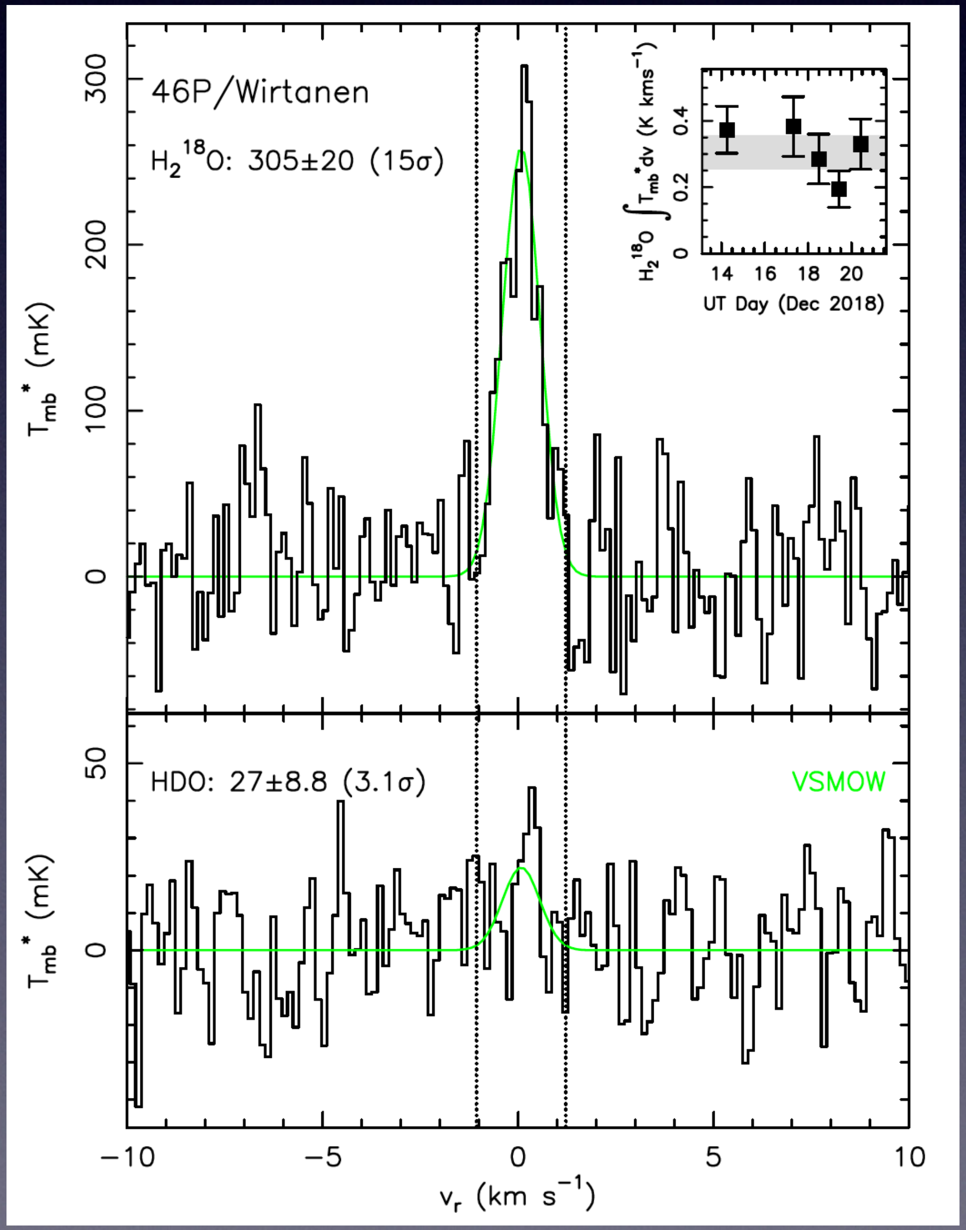


Durán et al. 2017

- HFA + LFA
- HFA + 4G

Comet 46P/Wirtanen

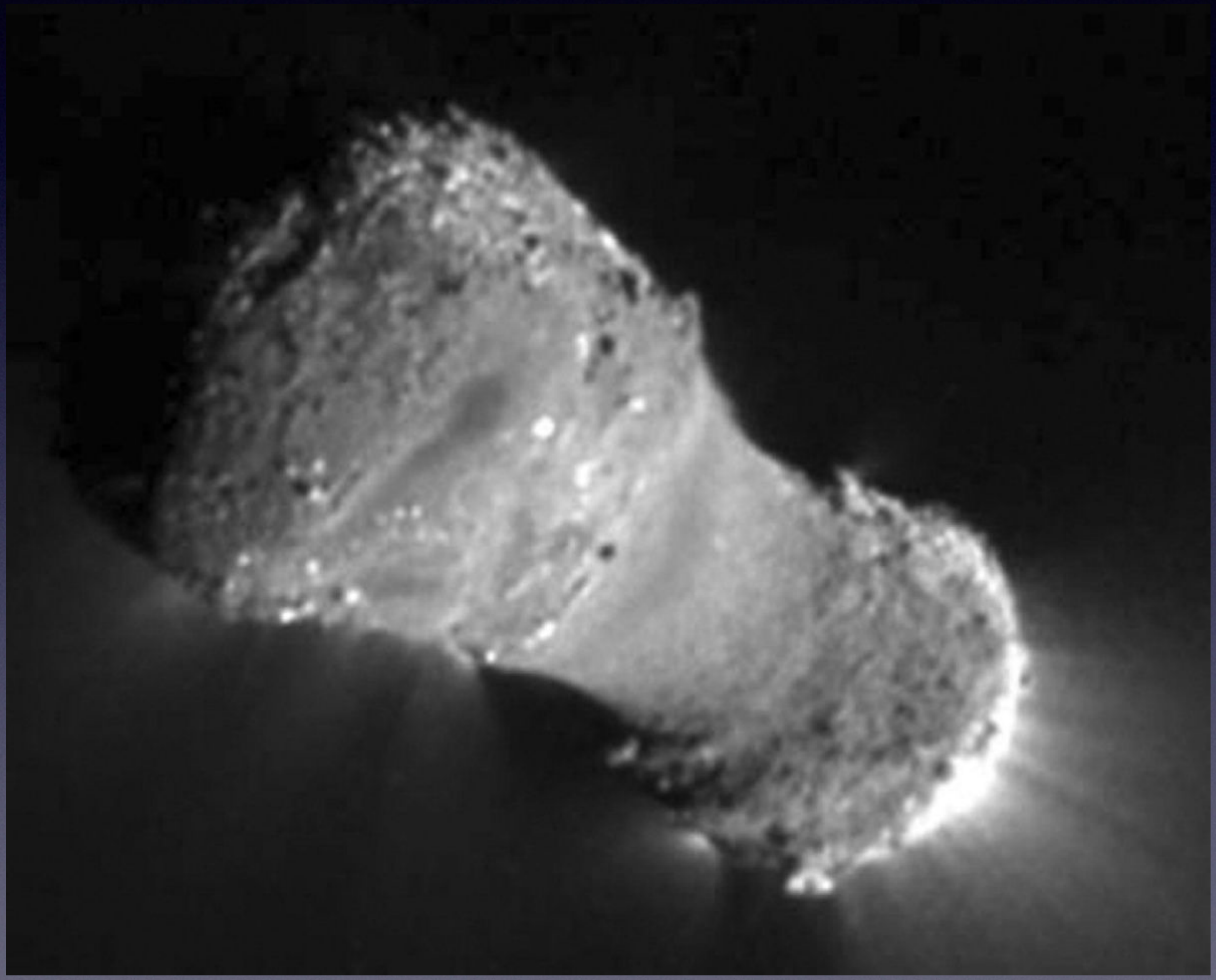
Image: V. Cheng



Lis et al. (2019)

- Perihelion on 12/12/18 at 1.055 au from the Sun
- Closest approach on 12/16/18 at 0.08 au from the Earth
- Five SOFIA flights between December 14 and 20 (GT+DDT)
- D/H = $(1.61 \pm 0.65) \times 10^{-4}$ including statistical, calibration, modeling, and $^{16}O/^{18}O$ ratio uncertainties
- Third Jupiter-family comet with a D/H ratio consistent with the Earth's ocean value
- What is special about the comets with a low D/H ratio?

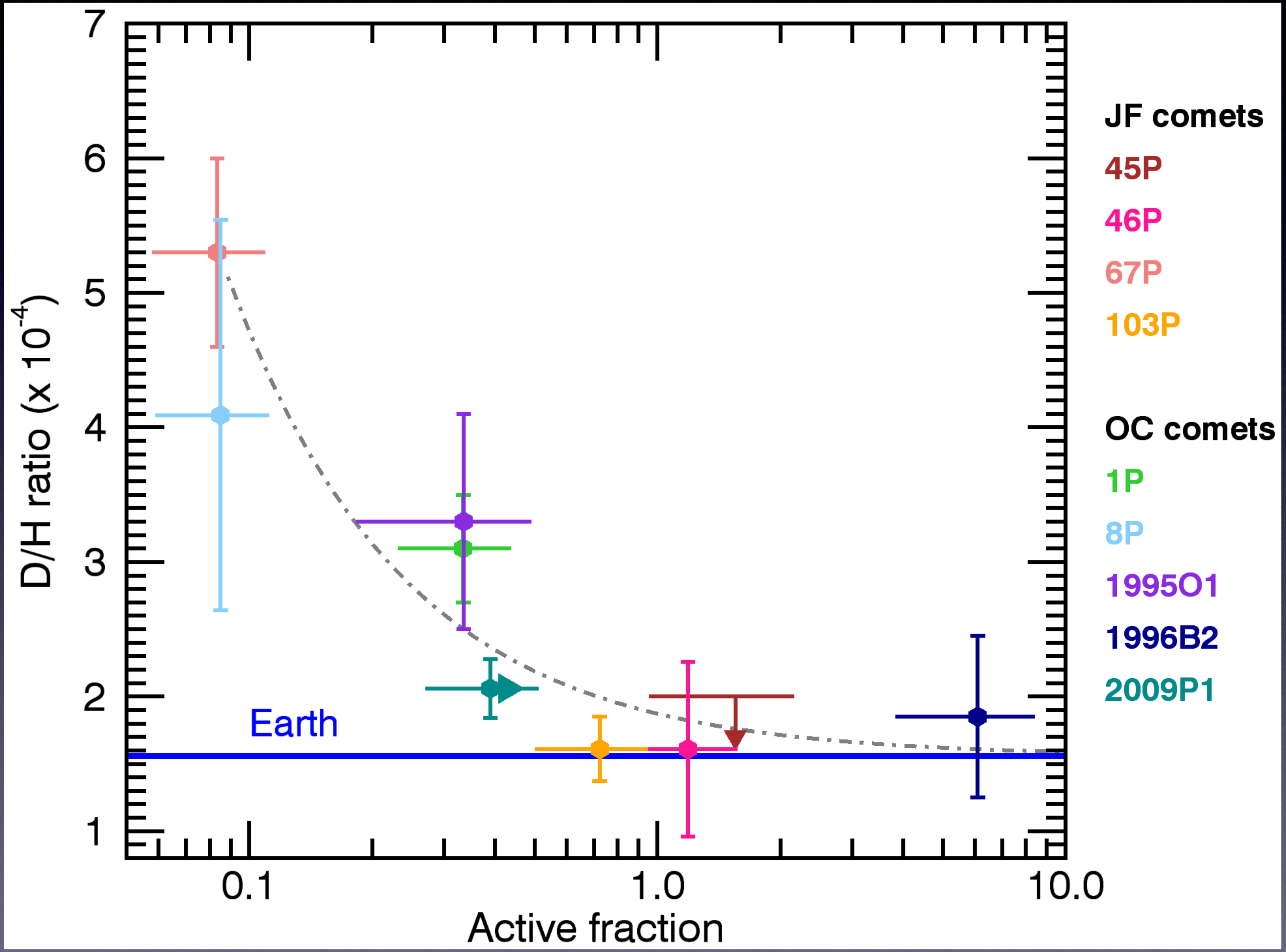
Hyperactive Comets



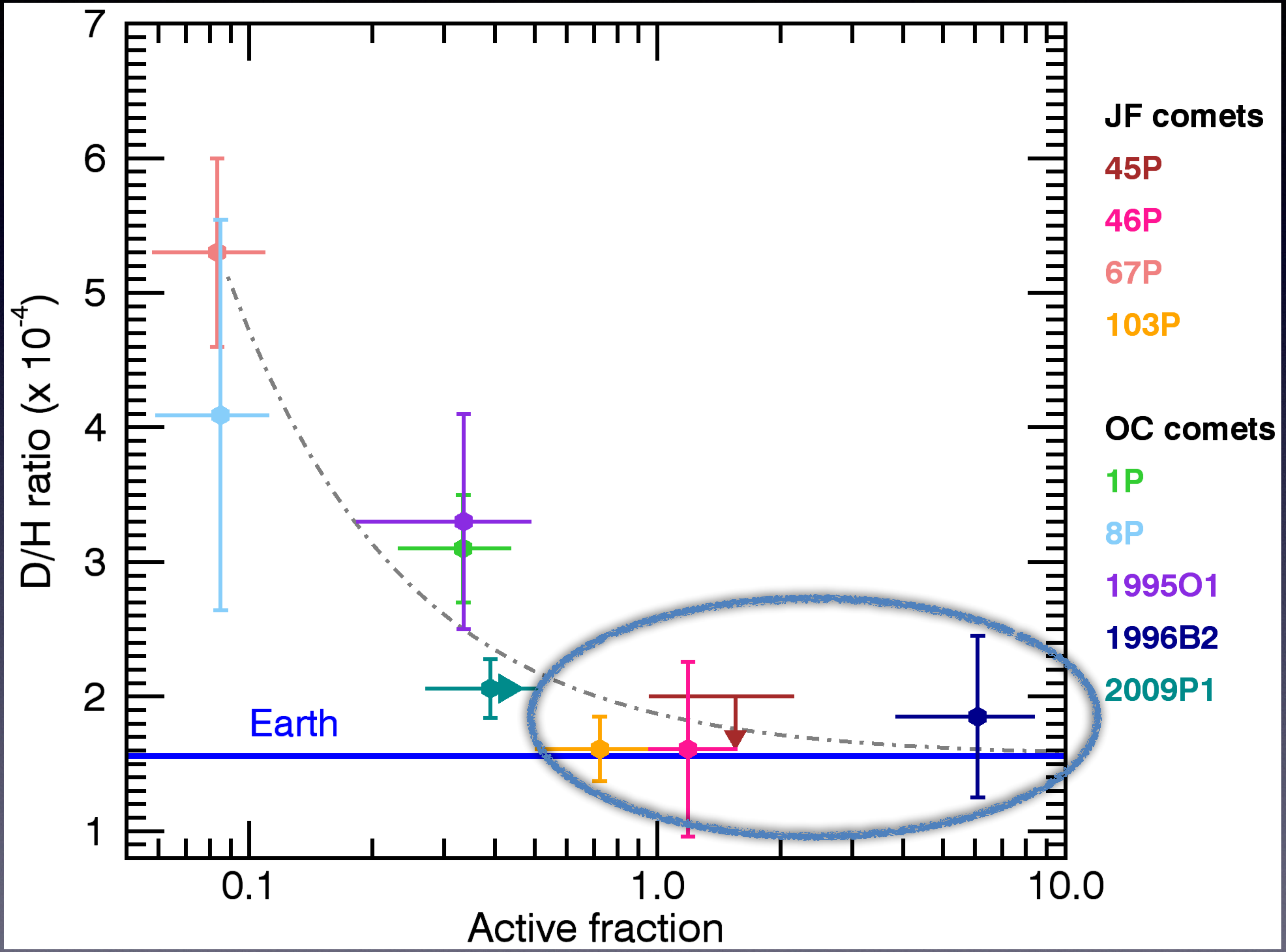
103P/Hartley — Deep Impact/EPOXI

- Emit more water molecules than can be expected given the size of the nucleus
- Presence of sublimating water-ice-rich particles in the coma
- Archetype 103P/Hartley studied by Deep Impact — both icy grains and water overproduction were observed
- Active fraction: ratio of the active surface area to the total nucleus surface
- A comprehensive set of water production rates from SWAN on SOHO (Combi et al. 2019)

D/H vs. Active Fraction

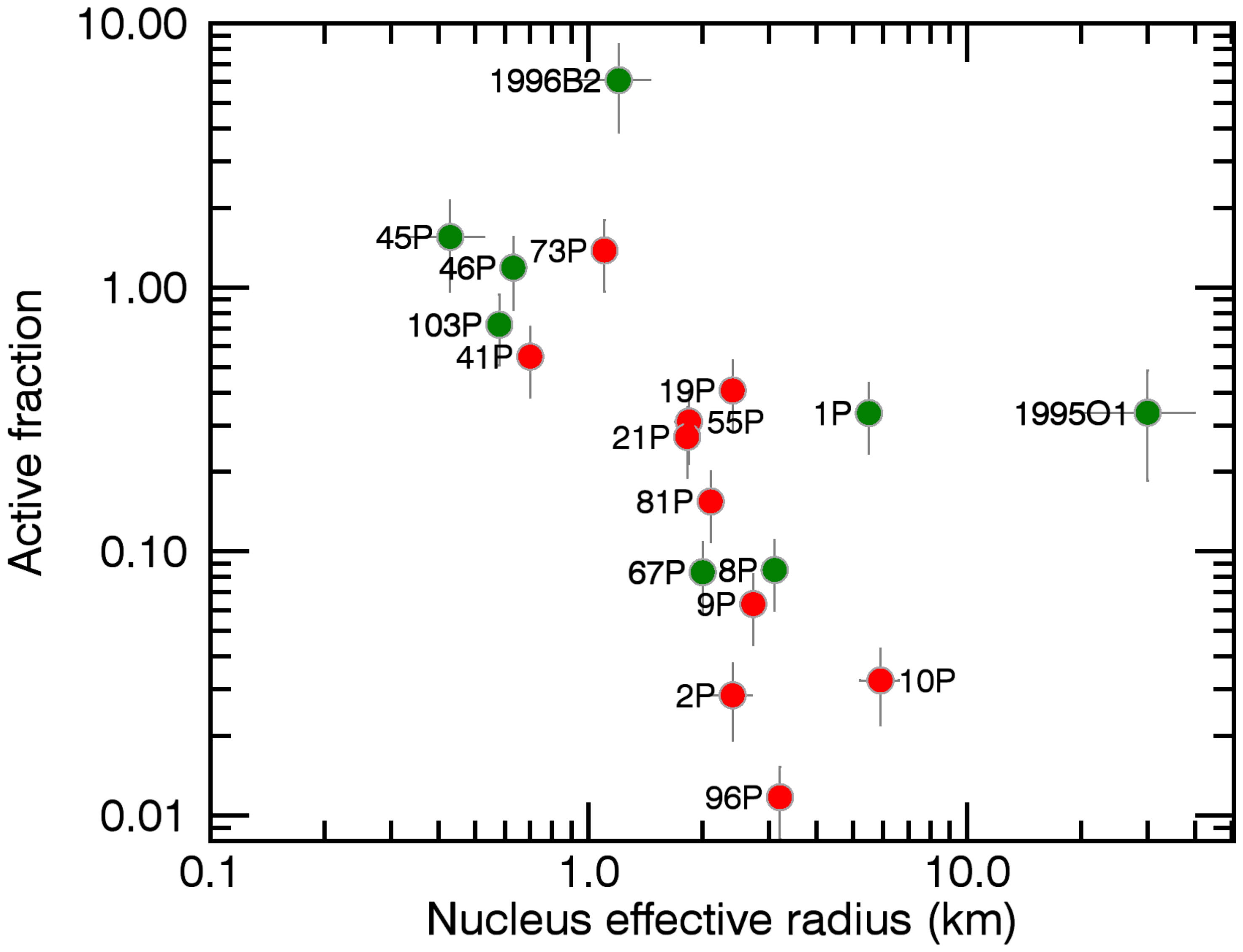


D/H vs. Active Fraction



- Comets with active fraction above 0.5 typically have terrestrial D/H ratios
- Large reservoir of ocean-like water in the outer Solar System

Possible Interpretations?



- Hyperactive comets are ice-rich objects that formed just outside the snow line
- Observed anti-correlation between active fraction and nucleus size argues against this
- Planetesimals outside the snow line are expected to undergo rapid growth

- Hyperactive comets formed in the outer Solar System from water thermally processed in the inner disk (Yang et al. model)

- Isotopic properties of water outgassed from the nucleus and icy grains may be different
- Need laboratory measurements

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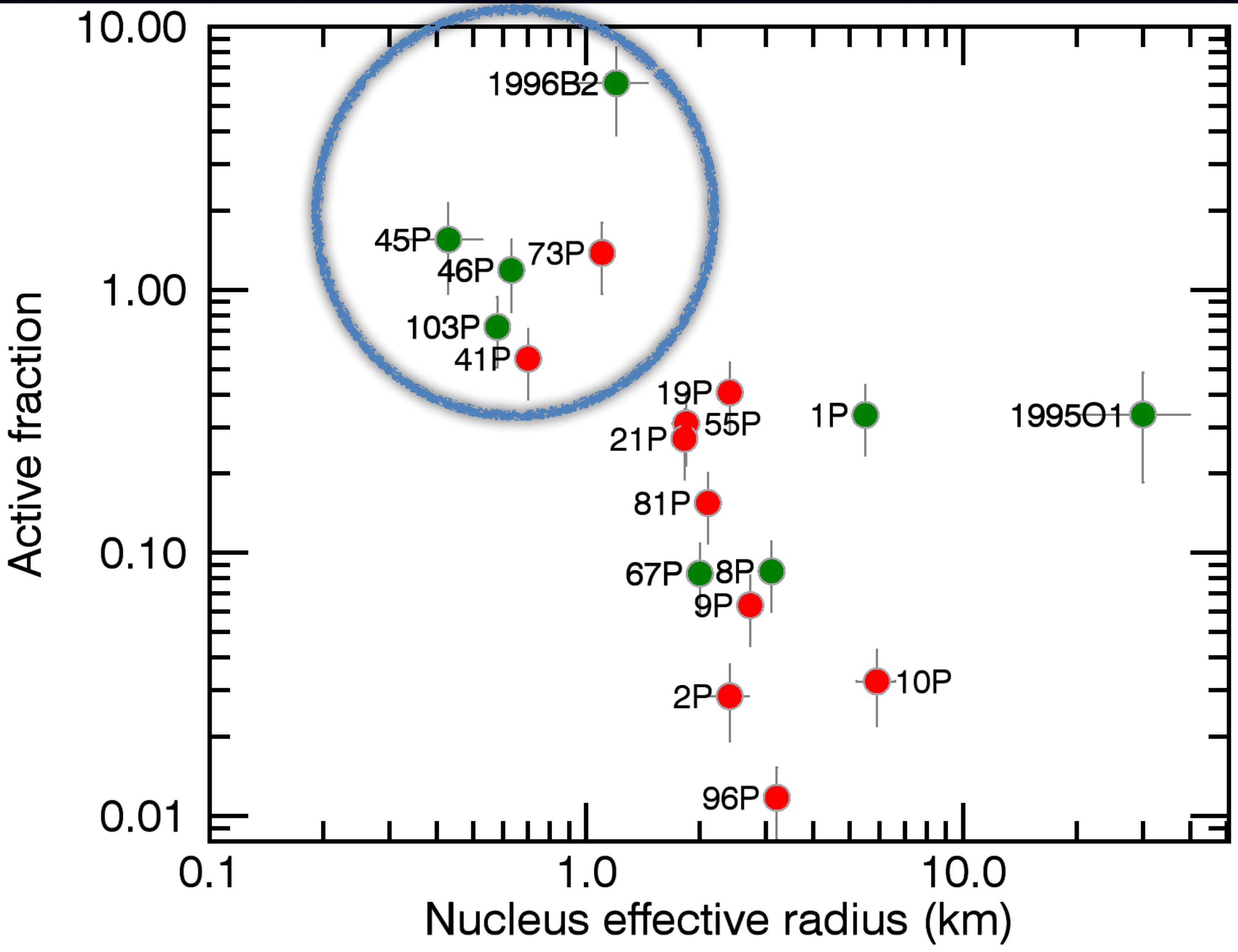

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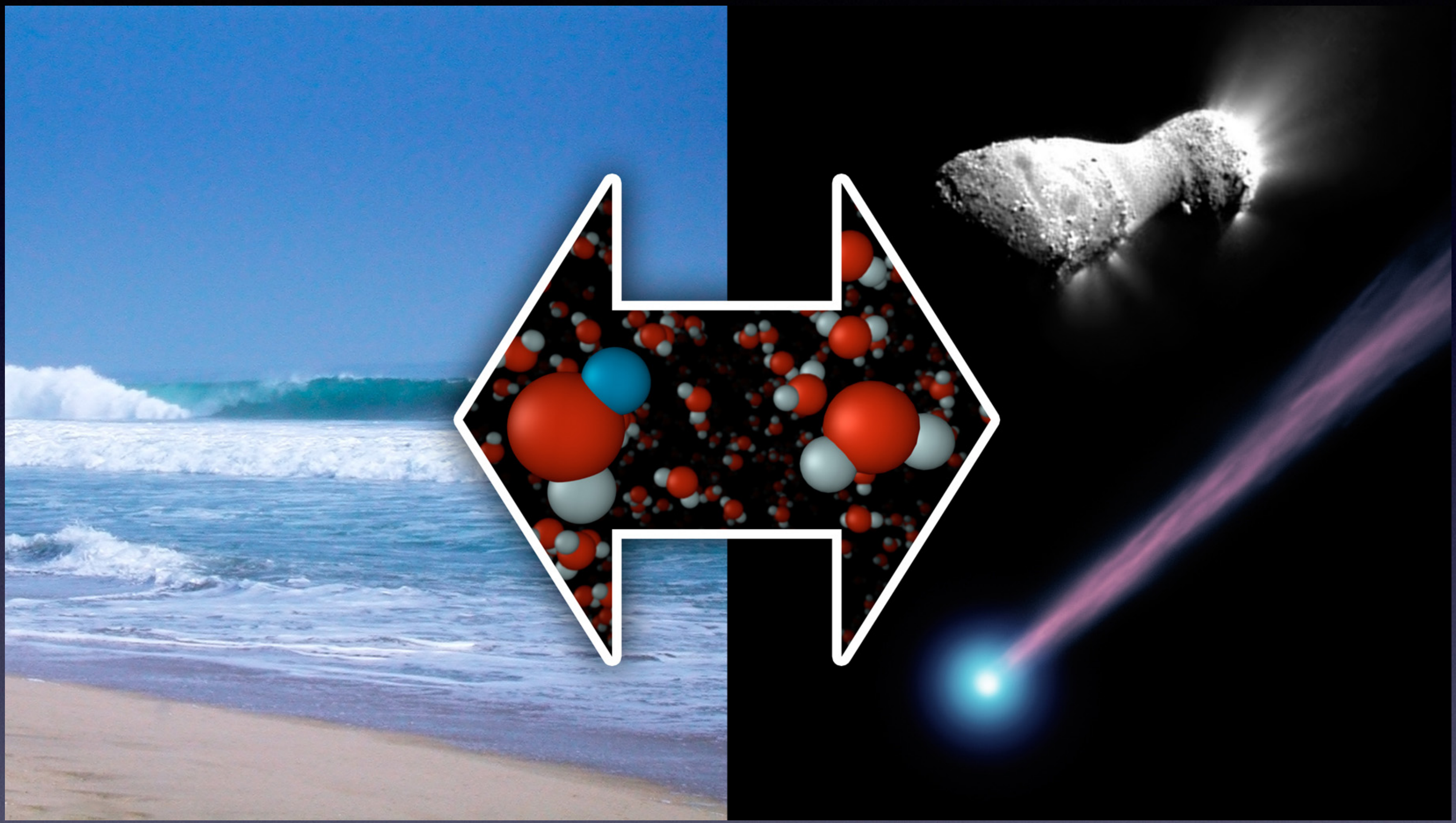
Way Forward?



- Measurements of isotopic ratios in a large sample of comets, including Main Belt comets, are key for understanding the origin of the Earth's water
- With a long term, focused program, SOFIA can double the number of existing D/H measurements during its lifetime (HIRMES — S. Milam's Teletalk on 1/15/20)
- *Origins* or a dedicated Discovery or Explorer class mission is needed to provide a statistically significant sample of measurements to accurately determine D/H in the outer Solar System

Jet Propulsion Laboratory
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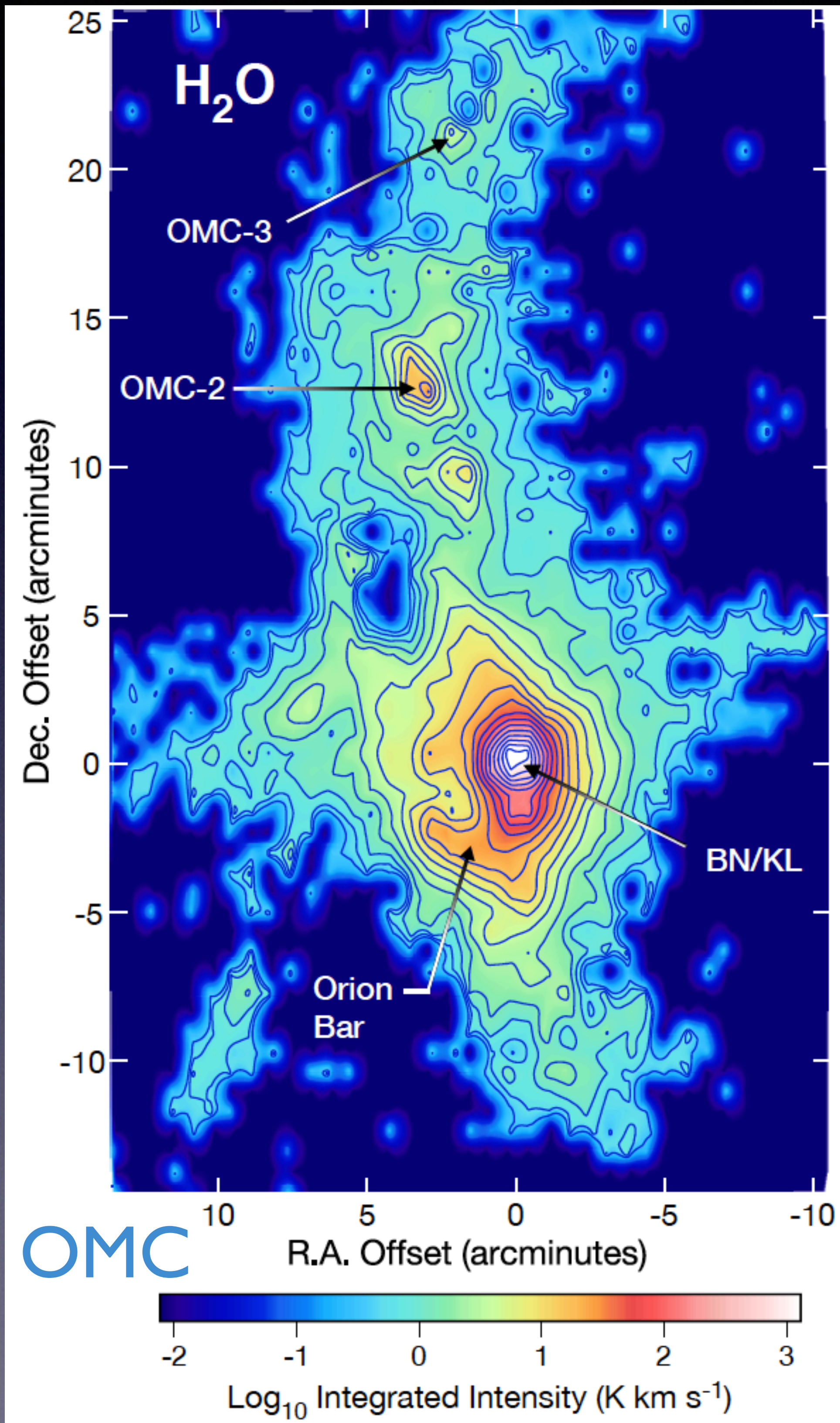
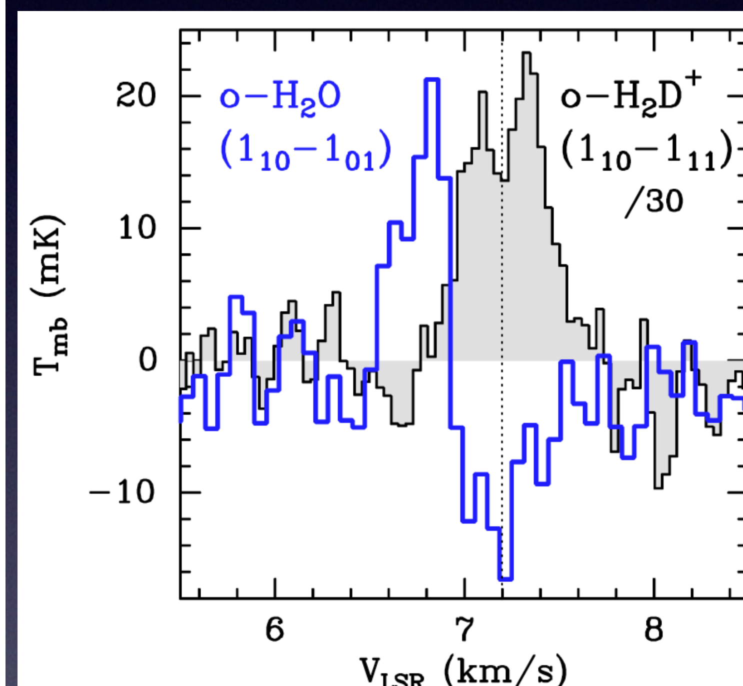
Backup Slides

Water Trail with Herschel



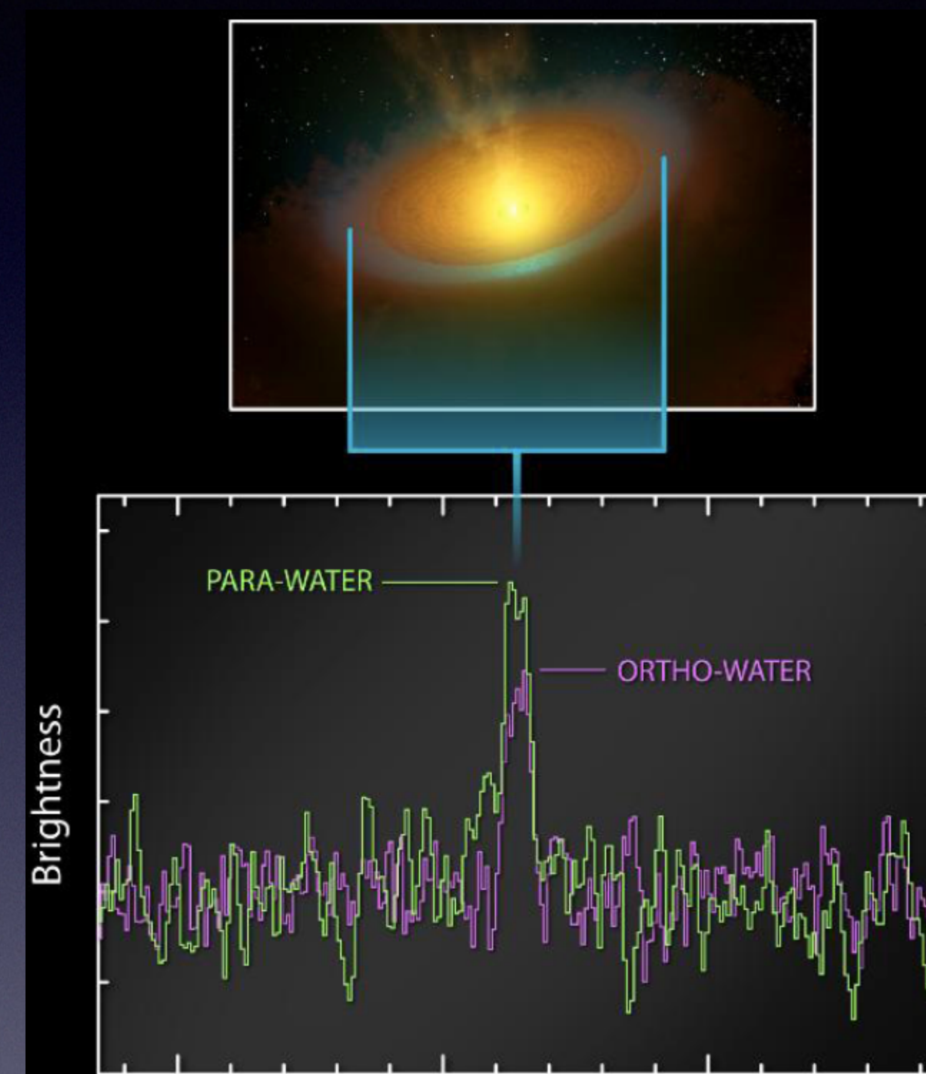
Melnick et al. 2019

L1544



Caselli et al. 2012

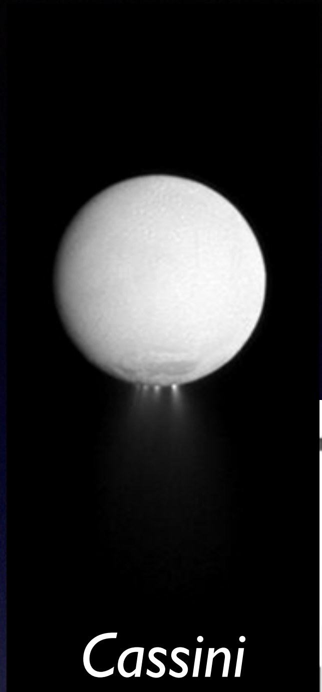
TW Hydrae

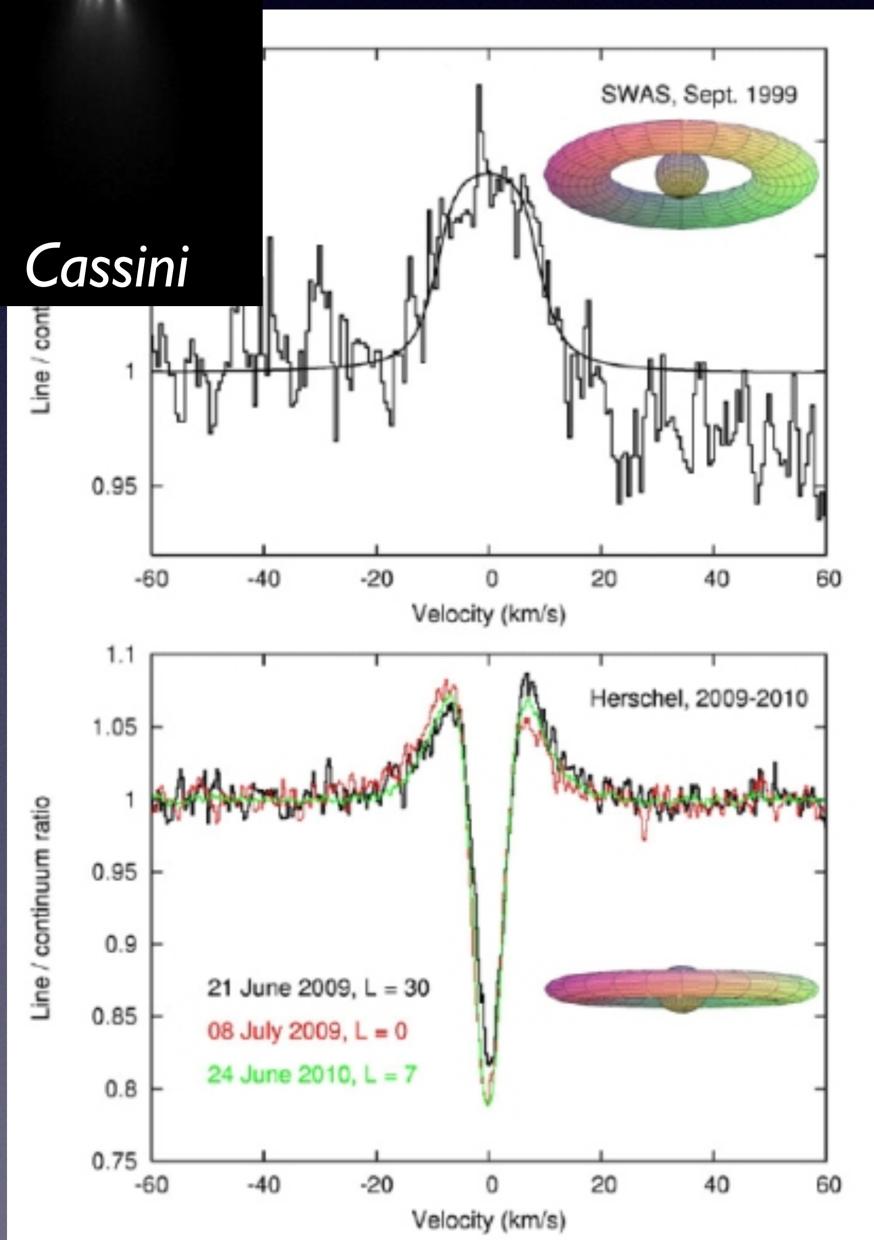


Hogerheijde et al. 2011

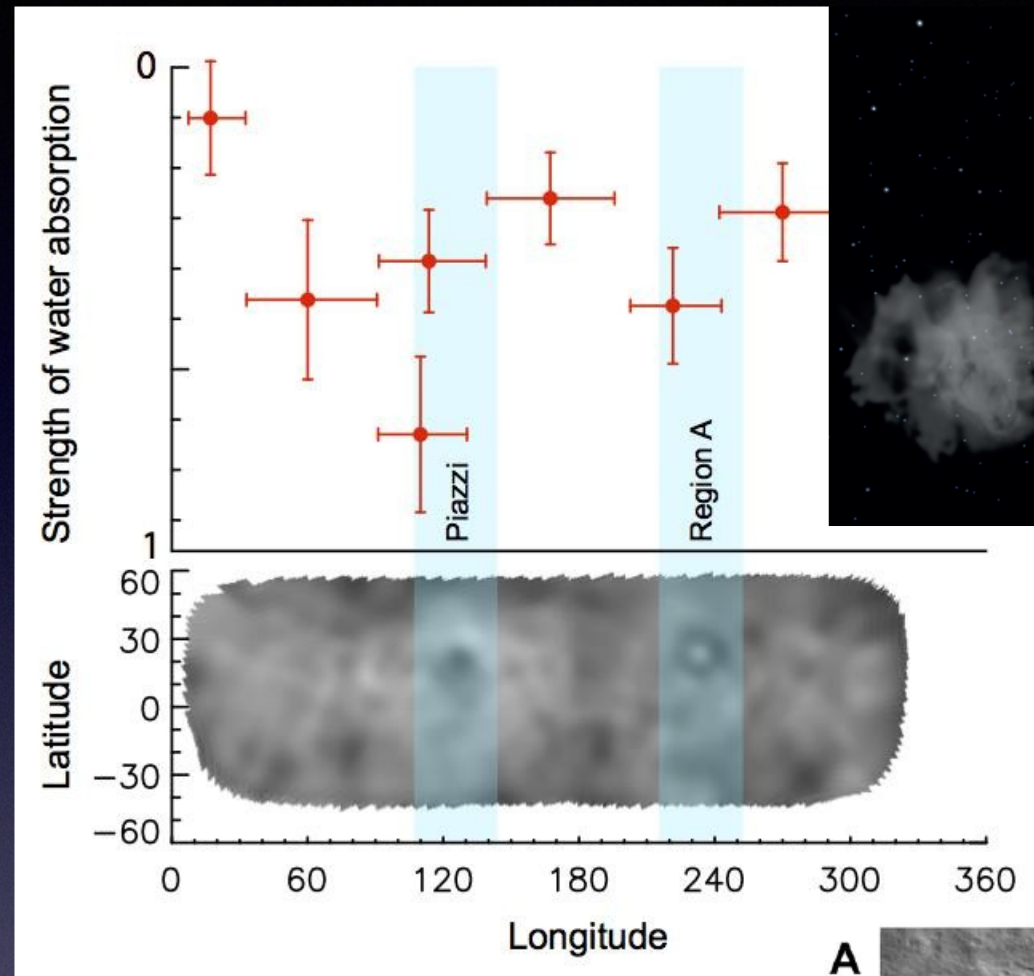
- Clouds ➟ Cores ➟Disks ➟ Planetary systems
- Origin of Solar System materials

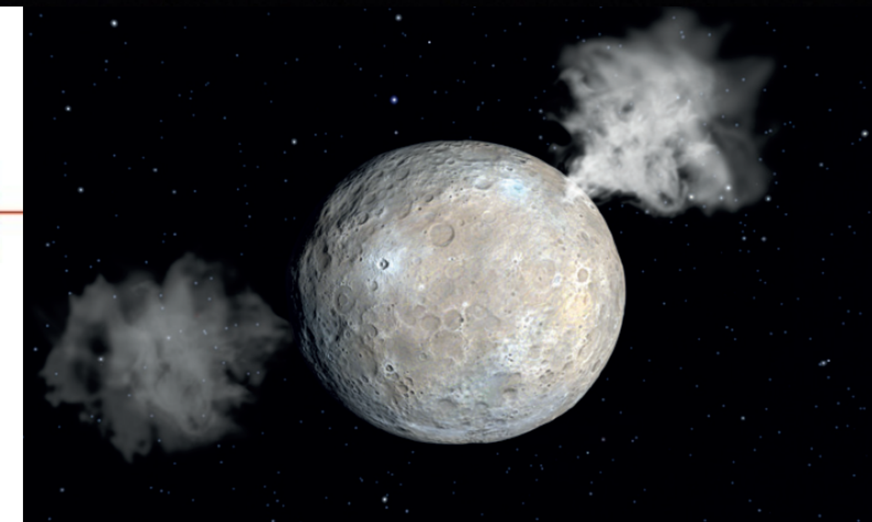
Water in the Solar System





Enceladus — Hartogh et al. 2011

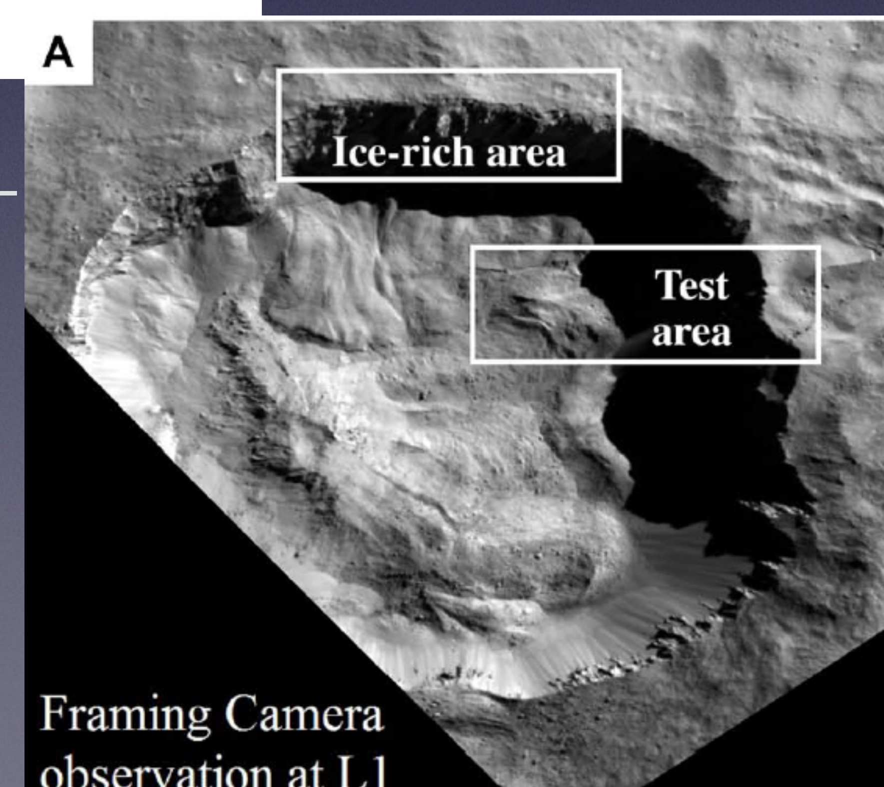




Cumpis 2014

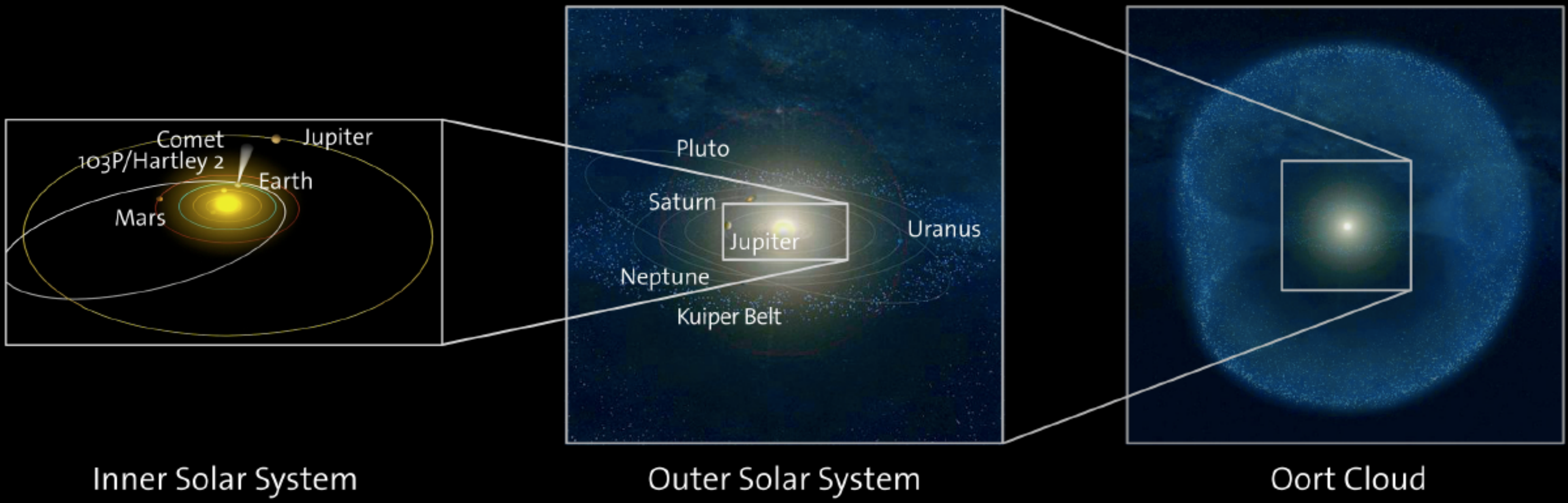
Ceres — Küppers et al. 2014

Dawn, Juling Crater — Raponi et al. 2018



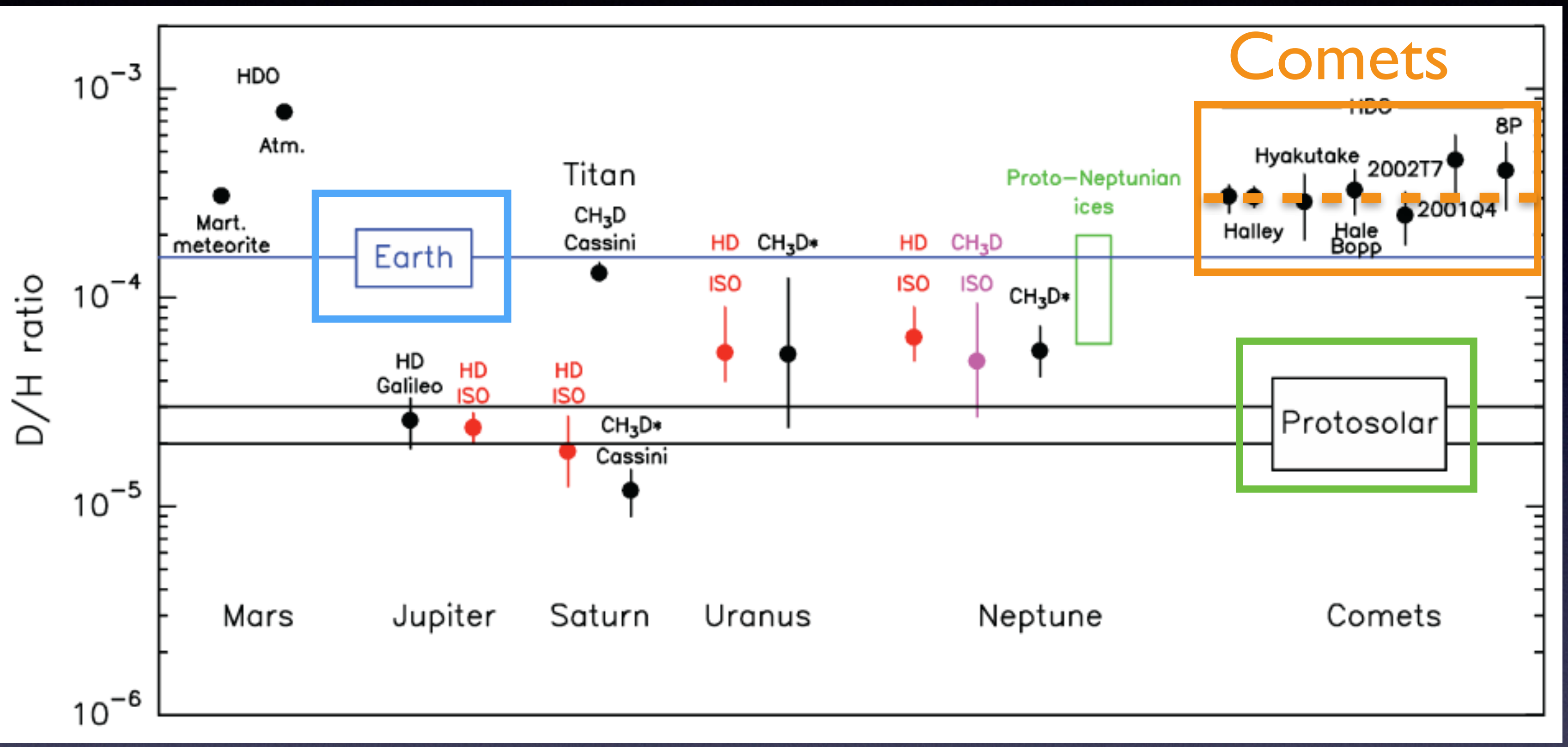
- Galilean satellites — origin of water in the atmosphere not well understood
- Main belt comets

Comets

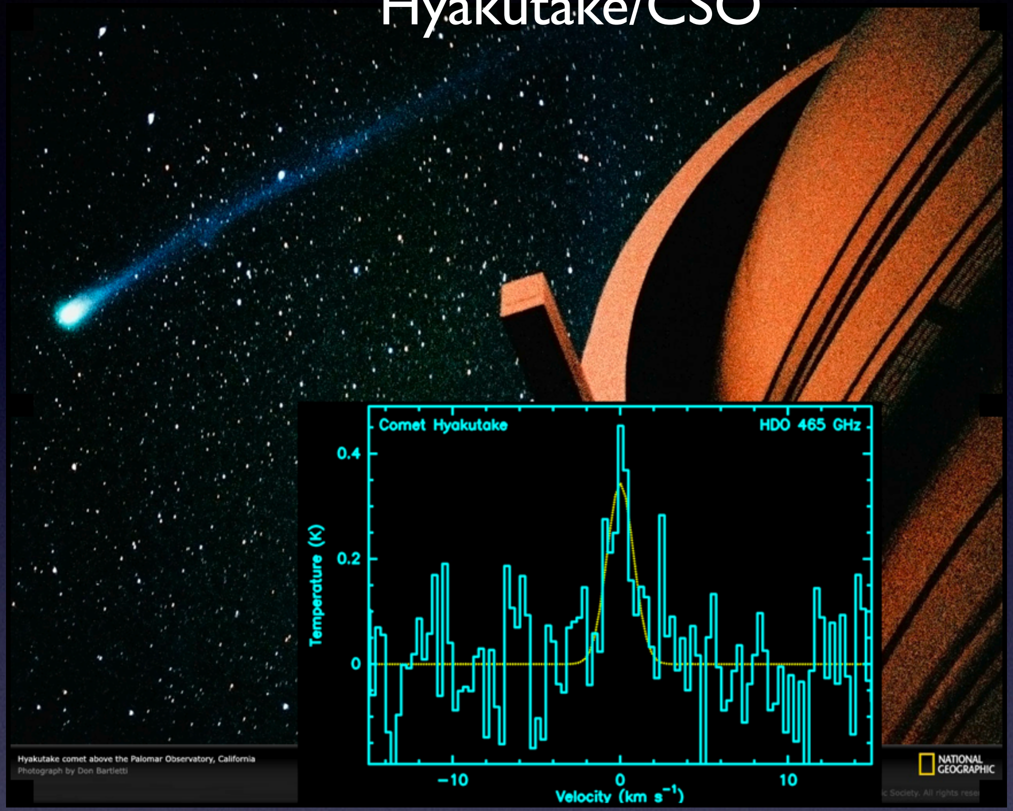


- Comets are among the most primitive bodies formed before planets and asteroids
- *Jupiter Family comets* originate in the Kuiper Belt, or associated scattered disc, beyond the orbit of Neptune
- *Long-period comets* come from the Oort cloud, but formed in the Jupiter-Neptune region
- Sent toward the Sun by gravitational perturbations from the outer planets or nearby stars, or due to collisions

D/H Pre-Herschel

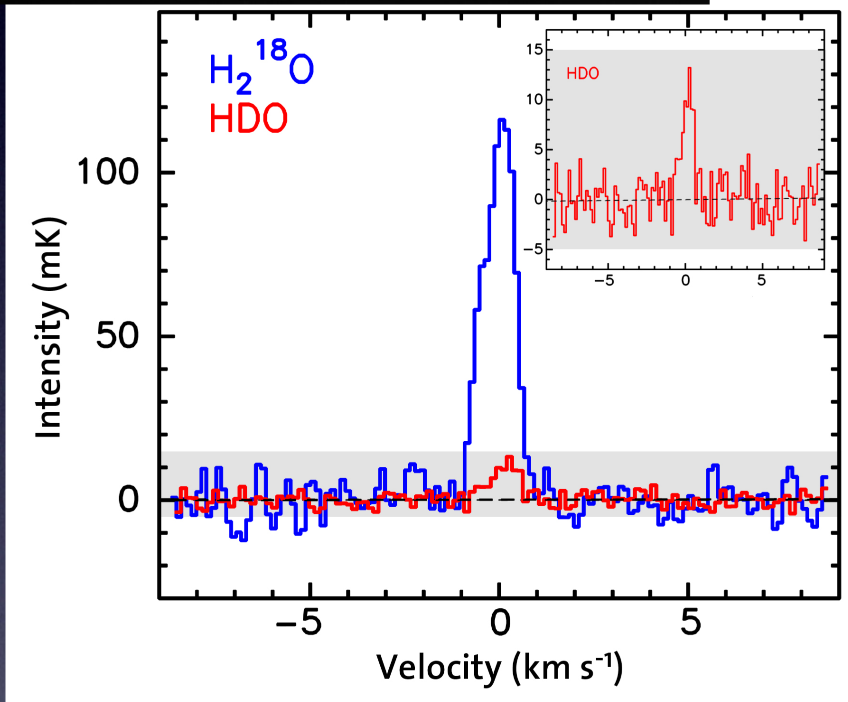


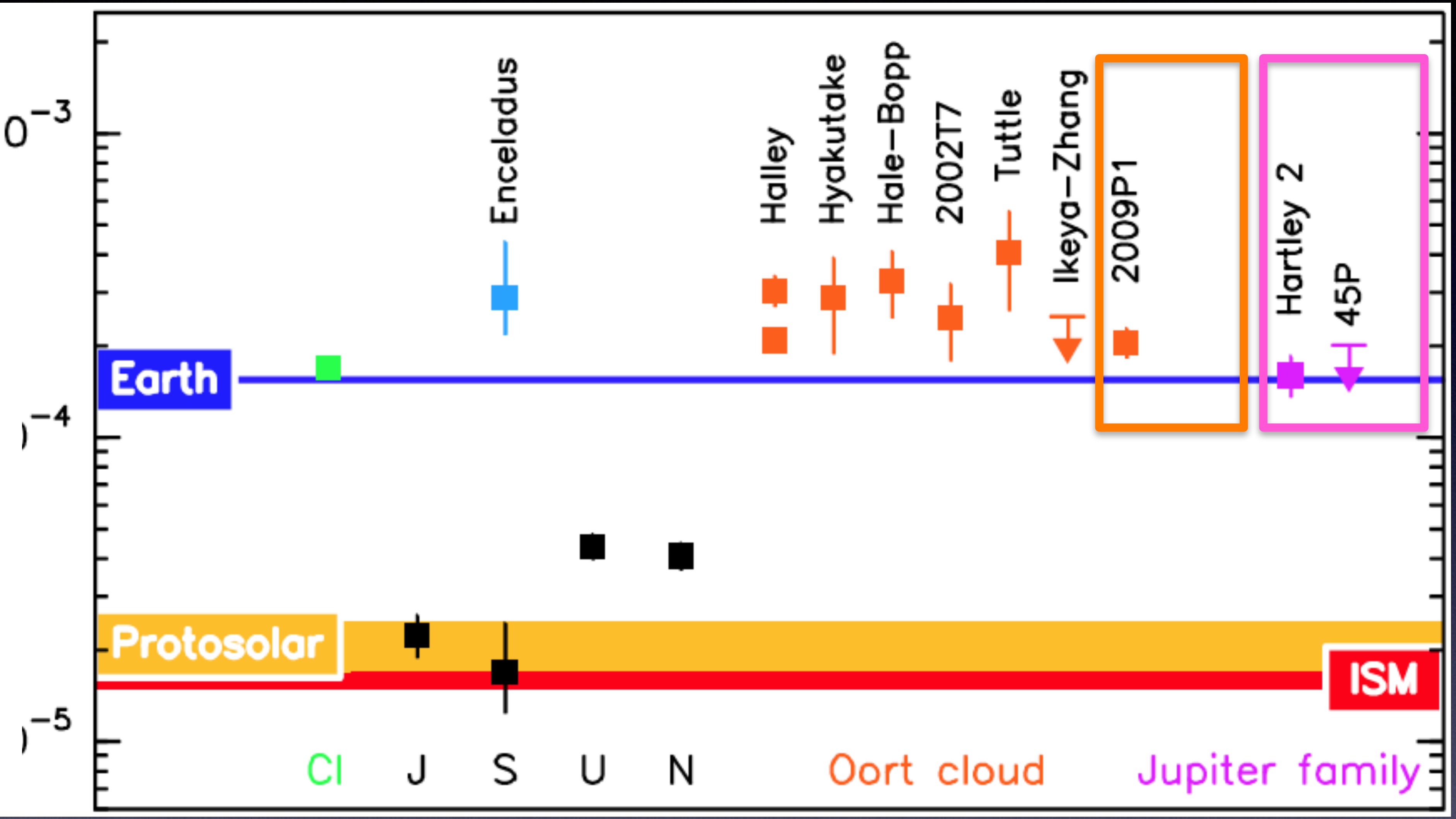
Hyakutake/CSO



- Protosolar D/H ratio in H_2 is ~2.5×10^{-5} (same as the Big Bang)
- Earth's ocean ratio (Vienna Standard Mean Ocean Water) is 1.56×10^{-4} — *Mantle water?*
- D/H in water in Oort cloud comets is ~3×10^{-4} — *Jupiter Family comets?*
- Most probable source of Earth water: ice-rich reservoir in the outer asteroid belt
- Comets could have contributed less than 10% of the Earth's water

D/H Herschel

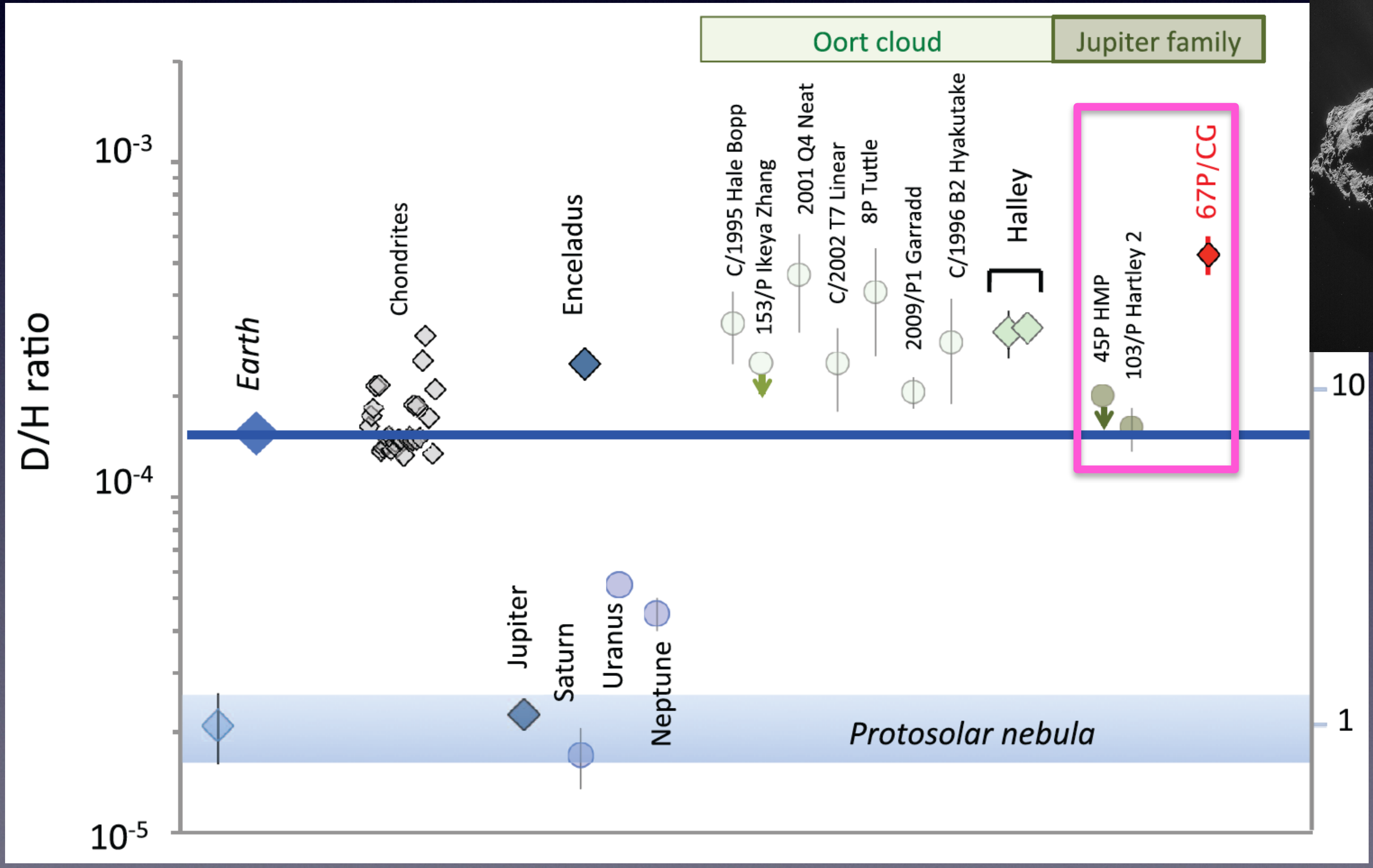


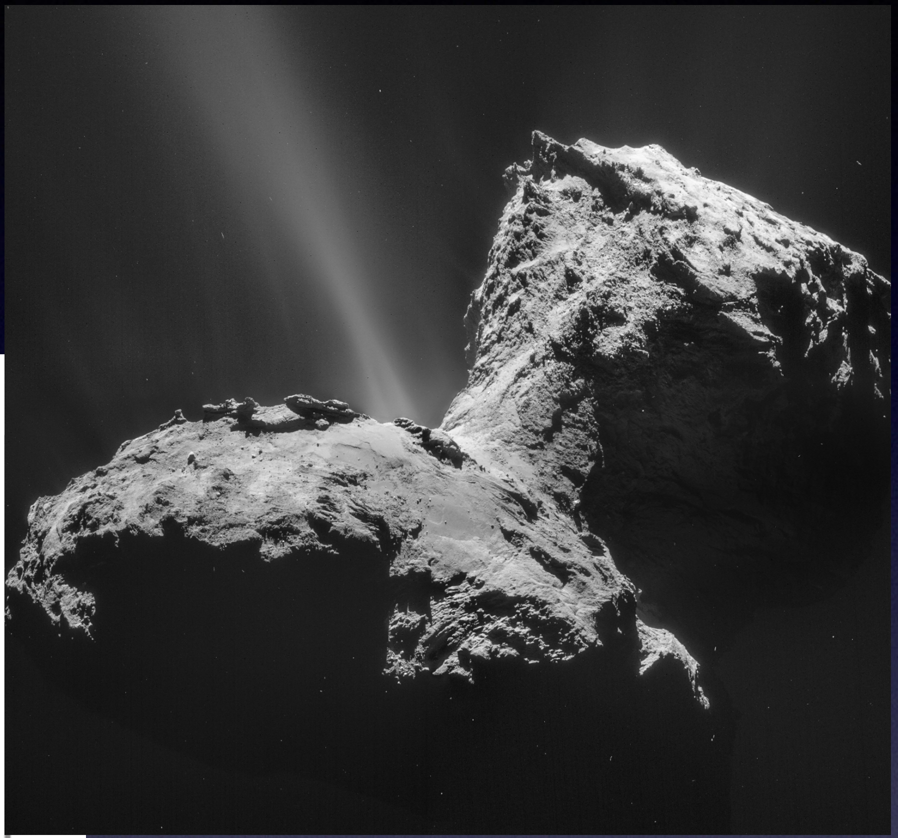


Hartogh et al. 2011, Lis et al. 2013, Bockelée-Morvan et al. 2012

- D/H in two Jupiter Family comets consistent with the VSMOV value
- A low D/H value measured in an Oort cloud comet
- The high pre-Herschel D/H values are *not representative* of all comets

D/H Rosetta





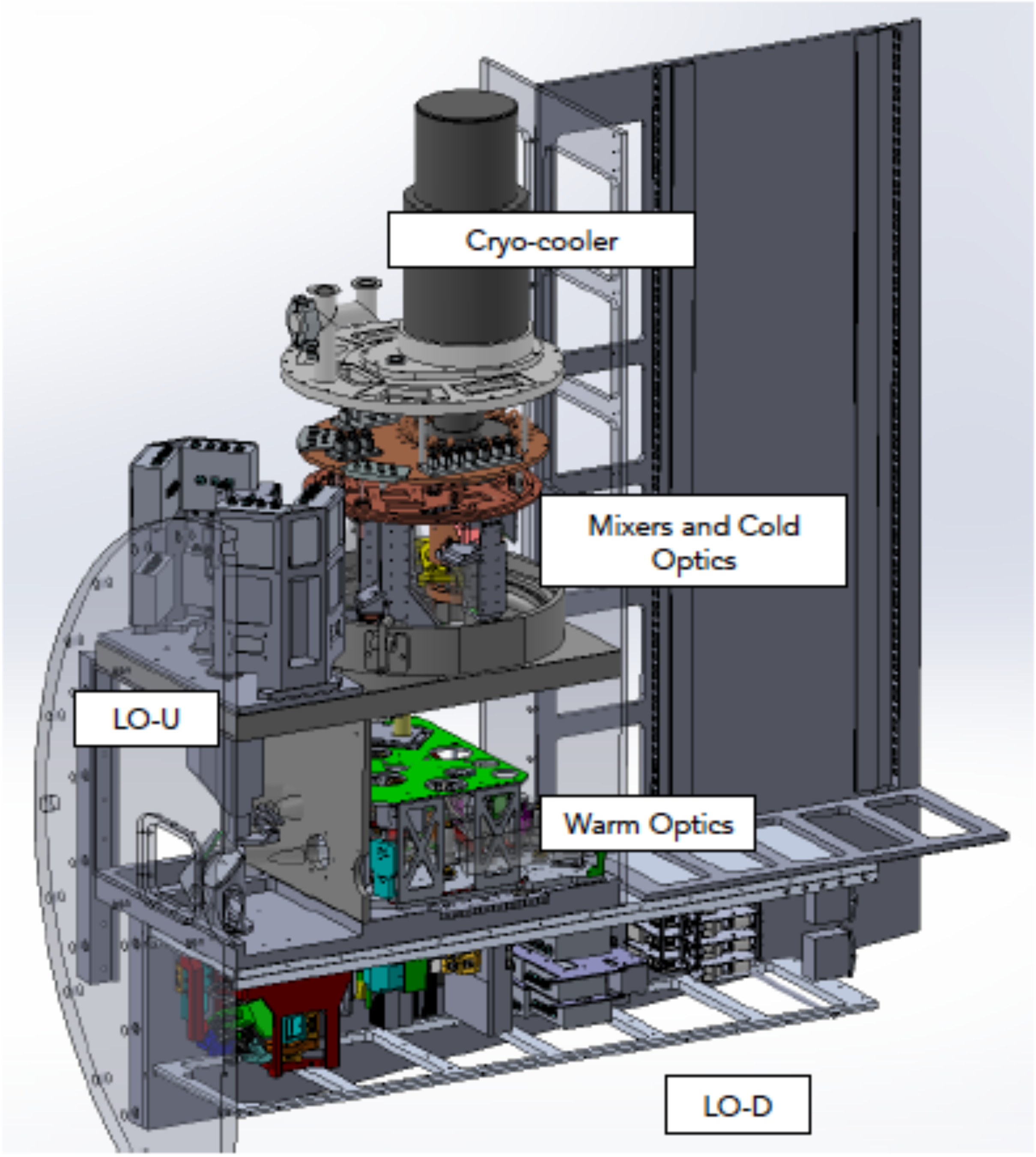
- Confirmed by Rosetta
- 67P Churyumov-Gerasimenko
- D/H three times VSMOW
- No trends with physical or dynamical parameters

Altwegg et al. 2015

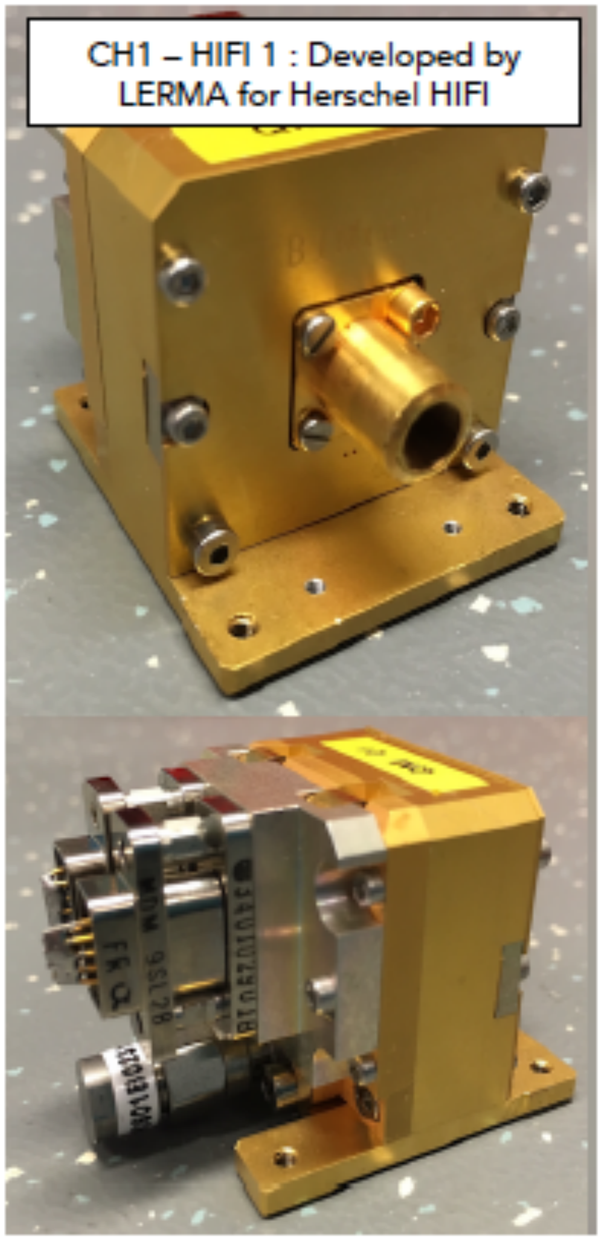
4GREAT: How does it look like?

- Operation in parallel with other "GREAT" cryostats
- 4 colors co-aligned on sky.
- The signal from sky is separated to feed the four detectors simultaneously
- Closed-cycle cooler
- Lowest frequency for CH1 : 492 GHz. Optics constraints.
- 4 individual solid state local oscillator sources, allowing independent tuning.

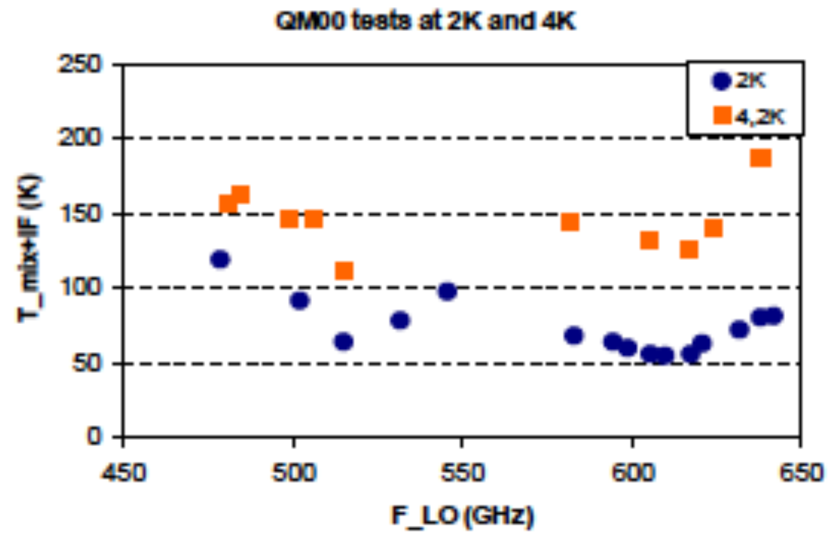
Durán et al. 2017



4GREAT: Mixers – SIS: CH1 and CH2

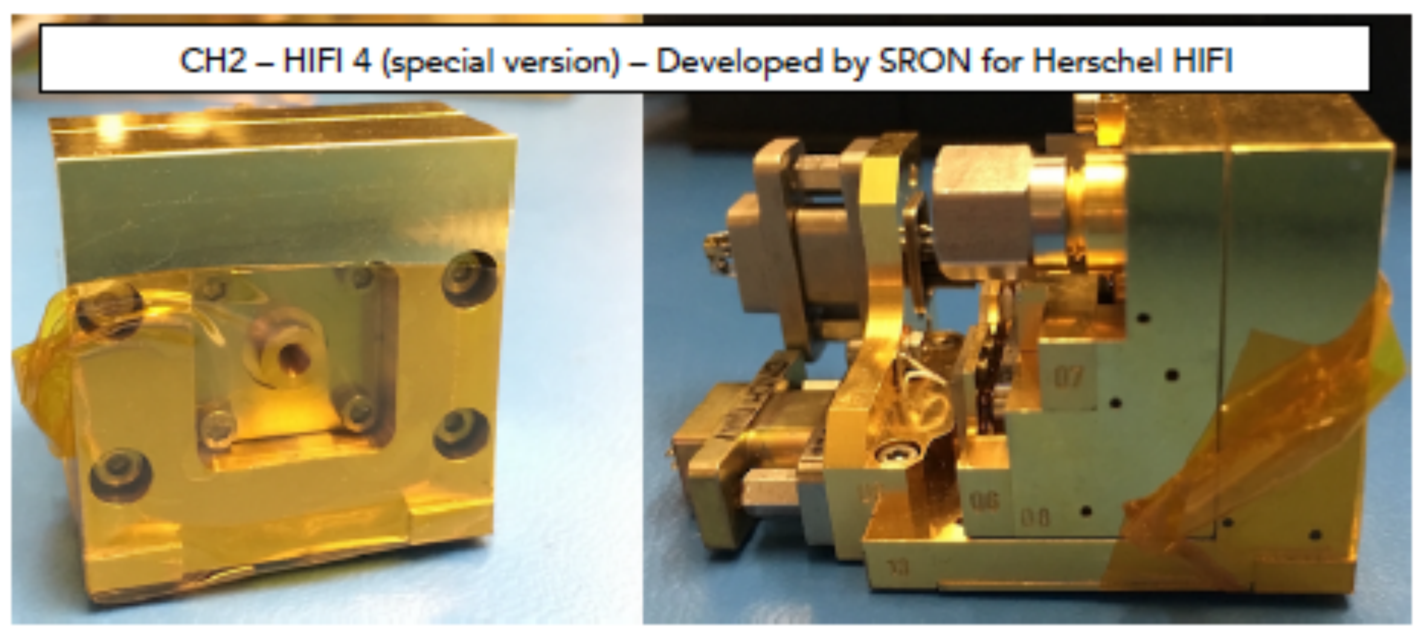


CH1 – HIFI 1 : Developed by LERMA for Herschel HIFI



Channel 1 - Noise temperature for QM00 at 2K and 4.2K. Data provided by LERMA

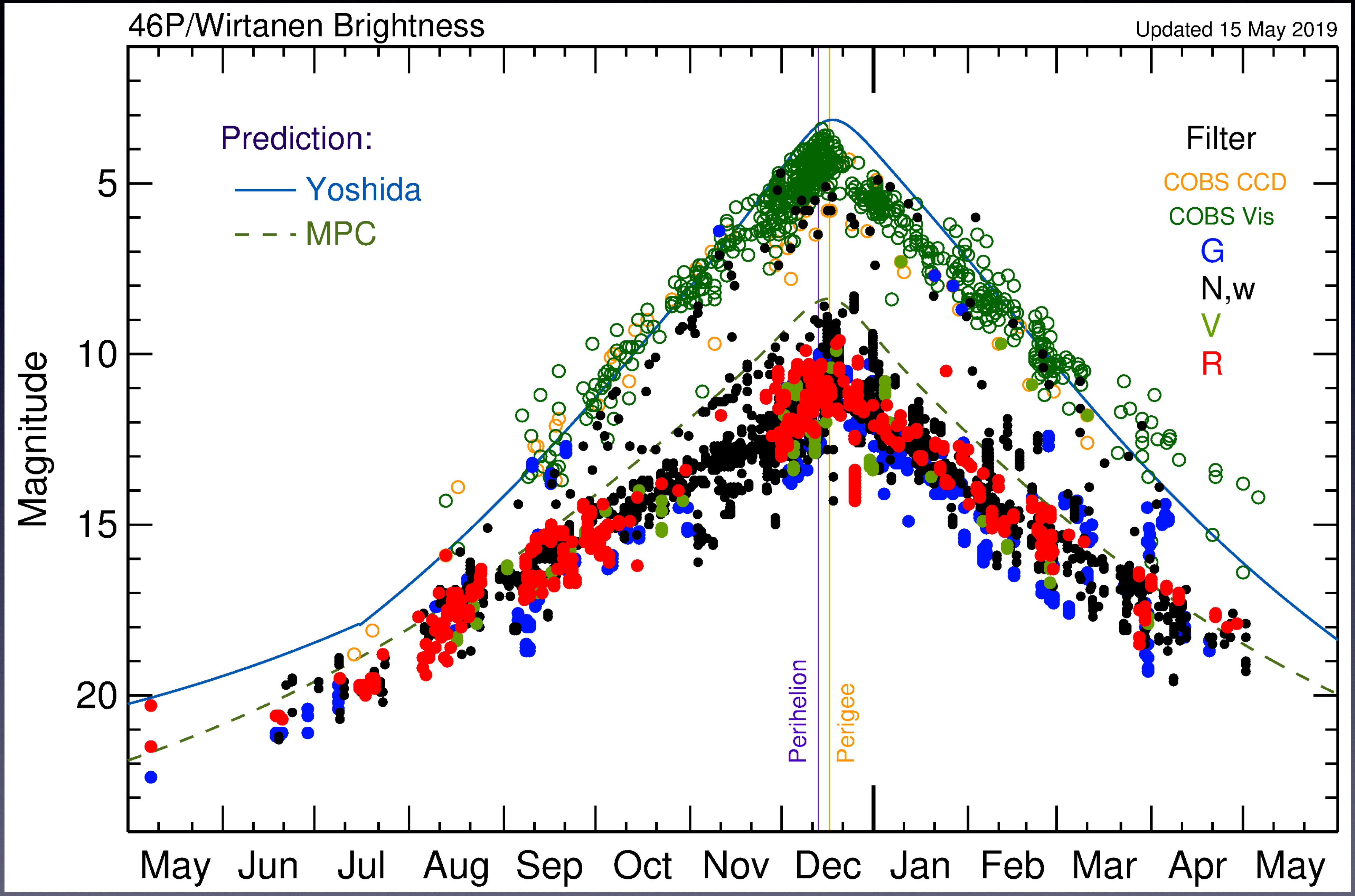
Band	Technology	Tsys	Manufacturer	Remark
CH1	SIS	300	LERMA	HIFI-1
CH2	SIS	500	SRON	HIFI-4



CH2 – HIFI 4 (special version) – Developed by SRON for Herschel HIFI

Durán et al. 2017

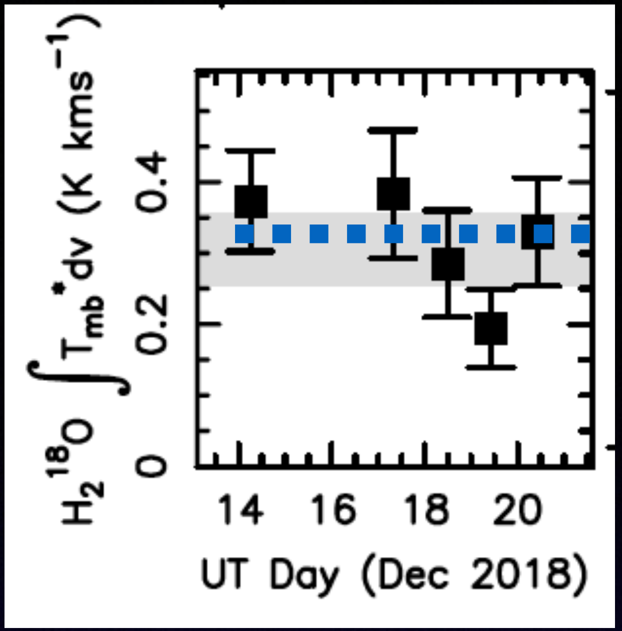
Wirtanen — December 2018



- Perihelion on December 12 at 1.055 au from the Sun
- Closest approach on December 16 at 0.08 au from the Earth
- Five SOFIA flights between December 14 and 20 (GT+DDT)

Image: U. Maryland

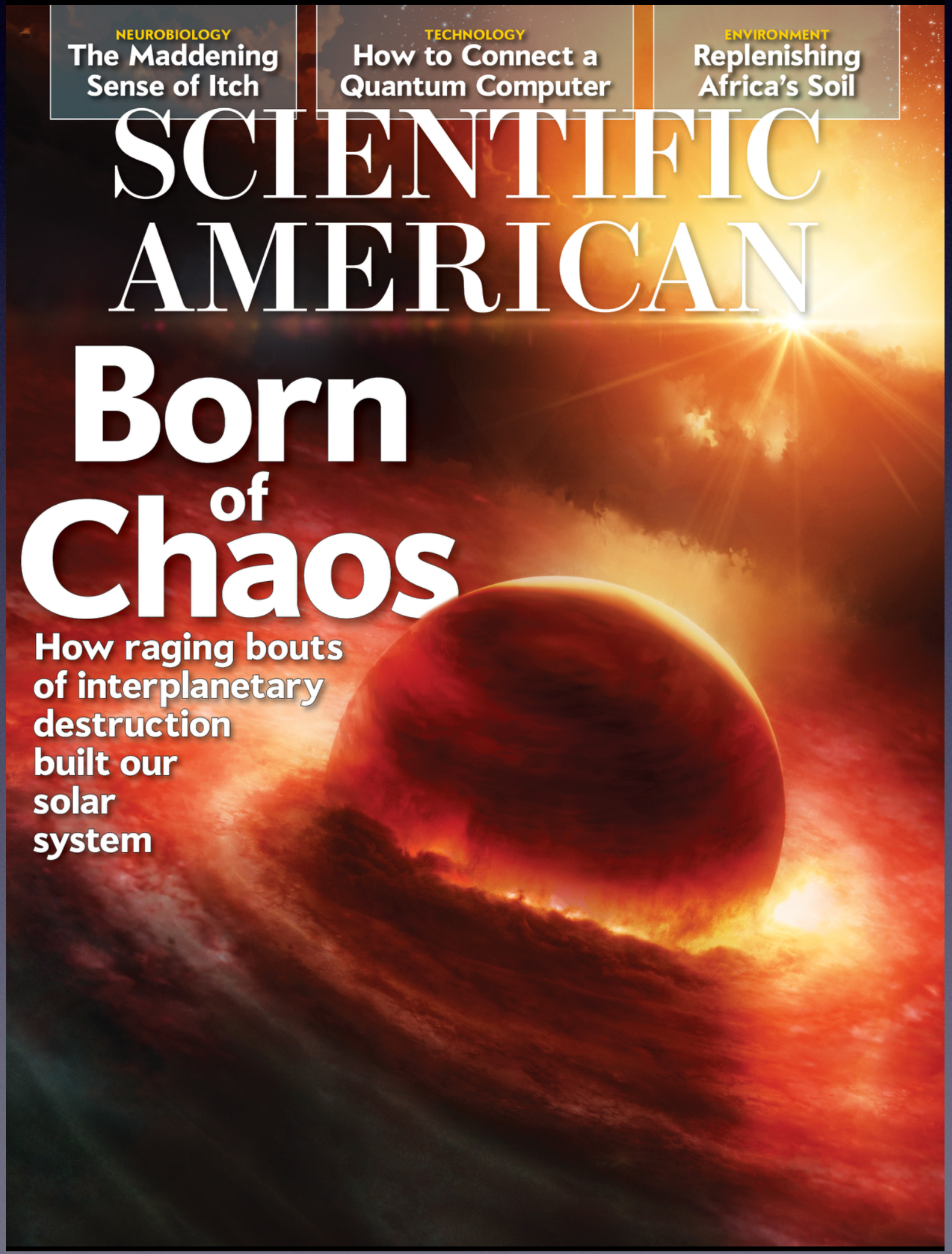
SOFIA Observations



Flight	UT time	r_h	Δ	$t(H_2{}^{18}O)$	$\sigma(H_2{}^{18}O)$	t(HDO)	σ(HDO)
	(hr)	(au)	(au)	(min)	(mK)	(min)	(mK)
1	Dec 14, 4.89–7.47	1.056	0.079	16.5	80	29.2	43
2	Dec 17, 7.56–9.68	1.057	0.078	7.2	125	30.8	38
3	Dec 18, 9.59–12.17	1.058	0.078	13.8	112	30.3	37
4	Dec 19, 9.78–12.00	1.059	0.079	14.9	85	25.6	42
5	Dec 20, 9.83–12.33	1.060	0.081	11.6	105	34.1	31

- Flight time ~3 h per flight — longest time allowed by the flight planning
- Total on-source integration time 64 and 150 min for $H_2{}^{18}O$ and HDO, respectively

Complex Solar System Dynamics



- Radiometric dates of major impact events on the Moon ~4 billion years ago
- "Late Heavy Bombardment" — 600 million years after Solar System formation
- Hard to explain in quiescent and stable Solar System